Net Power Generated by Flettner Rotor for Different Values of Wind Speed and Ship Speed

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***Abstract*—In global scenario, shipping and inland water transport became a very popular and necessary mode of goods transport, as it covers approximately 90% of the tonnage of all traded goods. That contributes approximately 2.8% to 3% of annual global greenhouse gas emissions, especially CO_2. The marine transportation is expected to increase further more as energy demand is expected to grow by 25% from 2014 to 2040. Environmental concerns for the reduction of CO_2 emission compel the shipping industry to reduce fossil fuel consumptions by increasing efficiency in shipping transportation and by adopting renewable energy sources for shipping. Wind energy for ship transportation is abundant and its potential is also high on seas. Wing sails, Airborne wind turbines, Wind kites, Flettner rotors, etc. are different techniques to harness wind energy for shipping. Flettner Rotor technique is one which provide thrust force for propelling the ship. In this paper, a cylindrical Flettner rotor (without endplates) of 12.5 m height and 2.1 m diameter is used for the theoretical analysis to estimate net power generation by Flettner rotor using the values of lift coefficient of C_L = 12.5 and drag coefficient of C_D = 0.2. Calculations have been made for ship speeds of 15 knots and 20 knots and wind speed variation from 5 m/s to 20 m/s at all true wind angles. Net power output obtained is maximum at true wind angles of 100 degree and 260 degree. At ship speed of 15 knots, the maximum values of net power obtained is 42.2 kW, 124 kW, 239.9 kW and 386.7 kW at wind speeds of 5 m/s, 10 m/s, 15 m/s, 20 m/s respectively. Whereas, at ship speed of 20 knots maximum values of net power is 68.2 kW, 189.5 kW, 358.8 kW and 575.2 kW at wind speeds of 5 m/s, 10 m/s, 15 m/s, 20 m/s respectively. Calculations have also been made for net power generation from Flettner rotor for various values of coefficient of rotation.**

Keywords—Flettner rotor; magnus effect; ship propulsion, wind energy.

I. INTRODUCTION

Freight transport covers approximately 90% of the tonnage of all traded goods, as per the International Chamber of Shipping [1]. According to the United Nations Conference on Trade and Development (UNCTAD) the global shipping tonnage load has increased by 3.05% compounded annually from 2.6 billion tonnes in 1970 to 9.5 billion tonnes in 2013. According to current estimates presented in Third IMO GHG Study 2014, international shipping emitted 796 million tonnes of CO_2 in 2012, which accounts for about 2.2% of the total emission volume for the same year. Also by domestic and other water transports there is some emission. By 2050 this will increase further more by anything between 50% and 250%, depending on future economic growth and energy developments [2]. Renewable energy sources can be utilised to reduce carbon emission due to shipping. As wind energy is the most abundant in shipping routes worldwide, researchers on Flettner rotor has renewed interest for applications of shipping transportation. Flettner rotor operates on the principle called Magnus effect.

This principle was given in 1852 by German scientist H.G. Magnus. According to this principle, when wind strikes the rotating cylinder, due to this rotational speed the cylinder accelerates air on one side and retards the air on the opposite side. A low pressure and a high-pressure region forms by this phenomenon. This resulting pressure difference develops a force called Lift force in the perpendicular direction to the wind flow and sense of rotation as shown in Fig. 1. The basic cause of the acceleration and deceleration is that the fluid layer near a solid surface has its velocity.

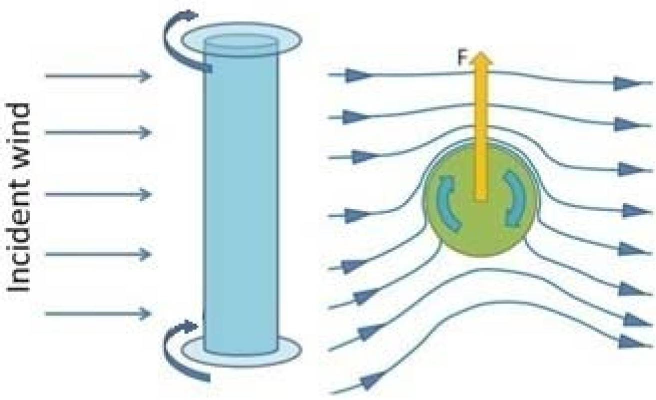

Fig. 1. Magnus Effect [3].

The lift force or thrust induced by the Magnus effect can be used as auxiliary propulsion system for ships if a cylinder is mounted on the ship deck appropriately and rotating it around its vertical axis. An electric motor system is used for rotation of the Rotor. The number of rotors can be varied with respect to the ship size, stability aspects, etc.

In this paper performance of the Flettner Rotor is analysed in terms net power generation and the effects of different parameters including kinematic and dynamic on net power

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generated by Flettner rotor is presented. This paper is divided into seven sections namely.

I. Introduction
II. Literature Review
III. System specifications
IV. Flow chart of the analysis
V. System Configuration and Formulation of Problem
VI. Results and discussion
VII. Conclusions

II. Literature Review

In the 1920's German Engineer, Anton Flettner, constructed a hypothetical theory of ship propulsion using the Magnus effect of a rotating cylinder. He patented his study namely "Flettner Rotor Ship Concept" on 16 September 1922 [4]. Flettner with his teammates A. Betz, L. Prandtl and J. Ackeret designed two cylinder shaped "sails" to propel the sailing ship "Buckau" in 1924. In 1926 Backau is modified to Barbara having three cylinders. But it got accident in 1929 [5].

Due to the cheap prices of fuel and the loss occurred in crash of Barabara shipbuilders were not attracted for manufacturing new kind of ship. Meanwhile some simultaneous developments took place like discs used by Alexander Thom in 1934 [6]. Dr. Wellicome [7] from Southampton University (1985) and Bergeson and Greenwald [8] in 1985 were one of the earliest researchers in recent times who reviewed different aspects of wind energy technology for marine transport. They concluded that Flettner rotors are the most efficient devices for wind assisted transportation.

In 2006, a number of students from the University of Flensburg under the guidance of Professor Lutz Feisser built a Flettner rotor driven proa [9].In 2008, Enercon, a wind energy company, designed and began construction on a Flettner powered cargo ship, named the E-Ship 1 to transport wind turbines among other products the company manufactures [10]. Another company from Finland namely, Norsepower has constructed a ship fitted with Flettner Rotor [11]. Different researchers worldwide are showing their interest in research on ship propulsion using flettner rotors.

Silvanius [12] from KTH centre for naval architecture, Traut et al. [13-14] from University of Manchester and Peter kindberg [15] from University of Michigan in 2015 compared the Flettner rotor with other wind energy assisted systems, while Craft et al. [16] (2012) from School of Mechanical, Aerospace & Civil Engineering, University of Manchester United Kingdom and Pearson [3] (2014) a naval engineer from UK gave their analysis on flettner rotor with and without discs.

III. System Specification

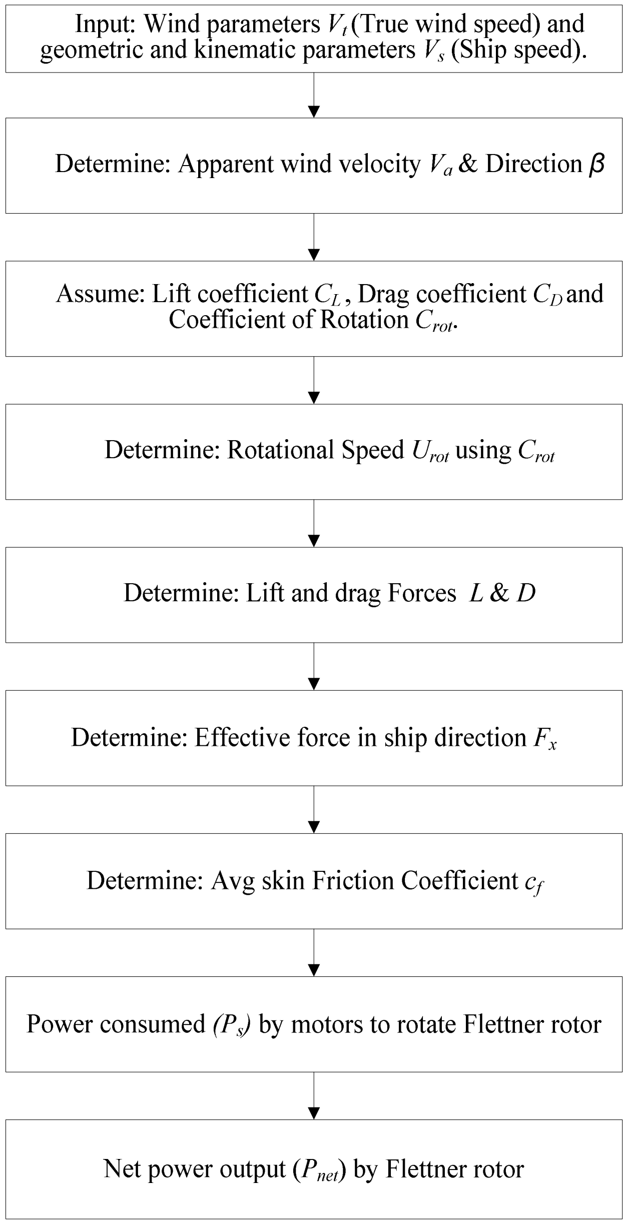
A. Flettner rotor

The Flettner rotor is an old technique that consist of one or more number of rotors that will be driven by electrical motor drives. In this study one Flettner rotor of 12.5 m height (h) and 2.1 m diameter (d) with aspect ratio (ratio of height of rotor to the diameter of rotor) of 6 is used for analysis [12]. The assumptions made for the system are tabulated in Table I.

TABLE I. Assumptions

Parameters	Assumed values
Co-efficient of lift C_L	12.5 [13-15]
Co-efficient of drag C_D	0.2 [13-15]
Density of air ρ_A	1.225 Kg/m^3
Dynamic viscosity of air μ	1.789×10^{-5} N-m/s^2
Efficiency of ship propulsion η_s	0.75 [12]
Drift angle λ	Neglected
Bearing friction	Neglected
Schlichting's formula used for skin friction coefficient (c_f) [17]	

IV. Flow Chart of the Analysis



V. System Configuration and Formulation of Problem

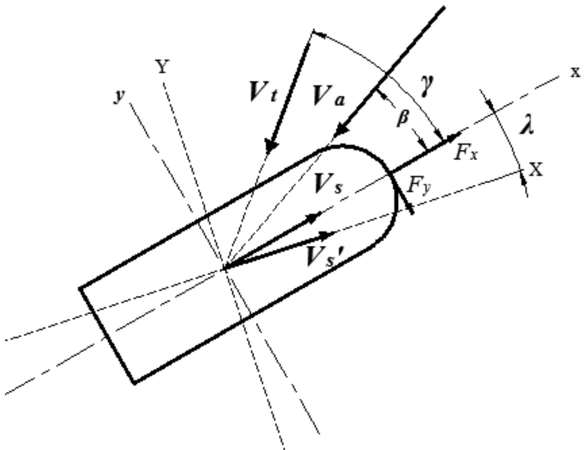


Fig. 2. Coordinate systems, forces and angles considered.

Variables and coordinates are defined and named in Fig. 2.

- F_x and F_y are the system generated forces by air.
- X and Y represents the global coordinates in which the ship moves.
- x and y represents the local coordinates.
- λ is the drift angle.
- γ is the true wind direction.
- β is the apparent wind direction.

The apparent wind speed V_a depends on the true wind speed V_t and the ship speed V_s which are known. The calculations have been made for very small drift angle (λ), so $V_{s'}$ coincides V_s.

The apparent wind speed V_a is given by eq. (1)

$$V_a = \sqrt{V_t^2 + V_s^2 - 2V_tV_s\cos\gamma} \tag{1}$$

The apparent wind direction β can be calculated by cosine law of velocity triangle,

$$\beta = \cos^{-1}\left(\frac{V_t^2 - V_a^2 - V_s^2}{-2V_aV_s}\right) \tag{2}$$

Velocity triangle is shown in Fig. 3.

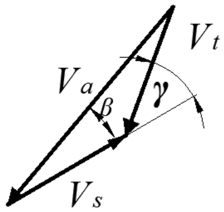


Fig. 3. Velocity Triangle.

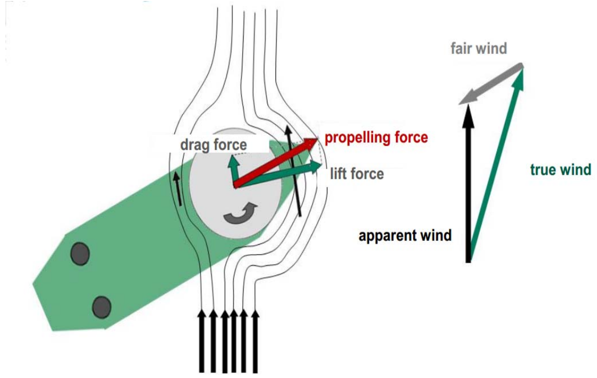


Fig. 4. The Magnus effect [18].

According to Magnus effect that is when a rotating cylinder hit by a free air stream a lift and a drag force induced which is shown in Fig 4. The forces are strictly dependent on the rotor size, angular velocity and free stream velocity.

While the air mass at one side of the rotor is accelerated, the air on the other side is decelerated. According to law of conservation of energy, this gives a lower pressure at one side and higher pressure on another side which creates the thrust force. This lift or thrust force per unit length ($L_{1/l}$) in terms of circulation Γ is given by Kutta-Joukowski law

$$L_{1/l} = \rho_A . V_a . \Gamma$$

Where Γ is circulation, $\Gamma = 2\pi\omega r^2$

ω is the angular velocity

r is the radius of the rotor

The coefficient C_{rot} is introduced as the relationship between rotational speed of rotor U_{rot} and the apparent wind speed V_a.

$$U_{rot} = C_{rot} . V_a \tag{3}$$

The rotational speed of rotor U_{rot} varies as apparent wind velocity V_a changes.

A. Power Consumed by Rotor:

The resistive force and rotational energy (power) required to overcome this resistance due to skin friction is estimated, by using the flat plate boundary layer theory. The Reynolds number Re, which is needed for calculation of frictional coefficient c_f, can be expressed as

$$\mathrm{Re} = \frac{\rho_A . C_{rot} . V_a . L_{\mathrm{Re}}}{\mu} \tag{4}$$

Where μ is the dynamic viscosity of air and L_{Re} is the characteristic length i.e. circumference of rotor (πd).

Now to find the skin friction coefficient or frictional drag c_f in terms of Reynolds number, we use Schlichting's formula which is valid for values of Re around 5×10^5 [18].

$$c_f = \frac{0.455}{(\log(\text{Re}))^{2.58}} - \frac{1700}{\text{Re}} \quad (5)$$

To calculate the total power needed to rotate the rotor the frictional force F_f needed is given by eq. (6)

$$F_f = c_f.\rho_A.\frac{U_{rot}^2}{2}.A_r \quad (6)$$

Where A_r is the surface area of the rotor (πdh)

Power required to rotate the rotor P_{con} is calculated as

$$P_{con} = F_f.U_{rot} \quad (7)$$

It should also be considered that this is a rough approximation and other factors like bearing friction will also increase the power needed.

The rotor is able to create a high lift coefficient depending on its rotational speed, but the disadvantage is that when higher lift is created the lift/drag ratio decreases and thus the drag increases. So we take $C_{rot} = 5$, $C_L = 12.5$ and $C_D = 0.2$.

B. Power from the System

Knowing the wind speed and wind direction it is possible to calculate the power from the system. This is performed by using the lift force L and drag force D of the system according to

$$L = p_o.A.C_L \quad (8)$$

$$D = p_o.A.C_D \quad (9)$$

Where C_L is the three dimensional lift coefficient

C_D is the three dimensional drag coefficient

A is the maximum projected area of the system

The stagnation pressure p_o is decided according to

$$p_o = \frac{\rho_A.V_a^2}{2} \quad (10)$$

Where ρ_A is the density of air

To determine the effective force in the direction of ship motion (x-x), F_x and in perpendicular direction (y-y), F_y, we resolve the lift and drag forces in ship moving direction and perpendicular to it. Representing F_x and F_y in matrix form

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} -D \\ L \end{bmatrix} \quad (11)$$

Or can be

$$F_x = L\sin\beta - D\cos\beta \quad (12)$$

$$F_y = L\cos\beta + D\sin\beta \quad (13)$$

F_x is calculated according to equation (12) with L and D are given as in equation (8) and (9) respectively.

System power (P_s) in ship direction is calculated by multiplying F_x and ship speed V_s.

$$P_s = F_x.V_s \quad (14)$$

The Net power output (P_{net})of the system

$$P_{net} = (P_s - P_{con}) \times \eta_s \quad (15)$$

Where η_s is the ship propulsion efficiency which is assumed to be 0.75.

VI. Results and Discussion

The initial calculations are done by taking the above constants and from the equations mentioned earlier at true wind speed of 5 m/s and ship speed of 15 knots (or 7.71 m/s) at all true wind angles from 0° to 360°. The performance of Flettner rotor depends on ship speed, wind speed, true wind angle and other aerodynamic parameters such as lift coefficient, drag coefficient and coefficient of rotation. The figures have been plotted using a polar graph for all true wind angles from 0° to 360°.

A. Effect of Wind Speed variation on power output at 15 knots ship speed when other parameters are kept constant:

As the true wind speed increased by 5 m/s, 10 m/s, 15 m/s to 20 m/s the net power output of the Flettner rotor increases as illustrated in Fig. 5. The other parameters C_{rot}=5, C_L = 12.5 and C_D = 0.2 are kept constant. However, the power consumption by rotor also increases but the net effect is positive as the generated thrust overcomes the resistive power.

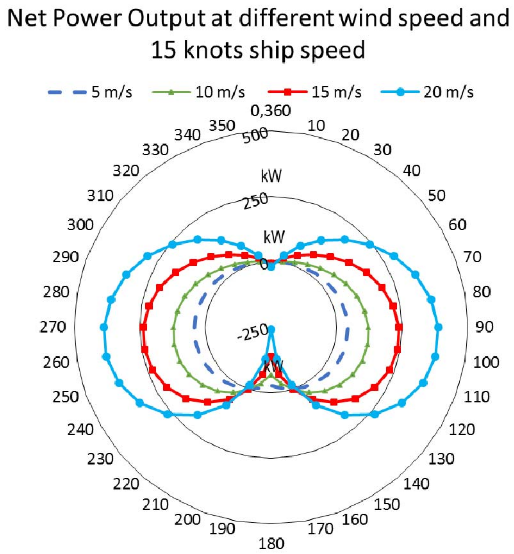


Fig. 5. Effect of Wind Speed variation on power output (kW) over all the true wind angle from 0° to 360° at 15 knots ship speed.

B. Effect of Wind Speed variation on power output at 20 knots ship speed when other parameters are kept constant.:

The effect of wind speed variation at all true wind angles is shown in Fig.6 at 20 knots ship speed. The other parameters

C_{rot}=5, C_L = 12.5 and C_D = 0.2 are kept constant. It is observed here that the variation pattern is same as in the previous case but the magnitude of net power is more when ship speed is increased from 15 knots to 20 knots.

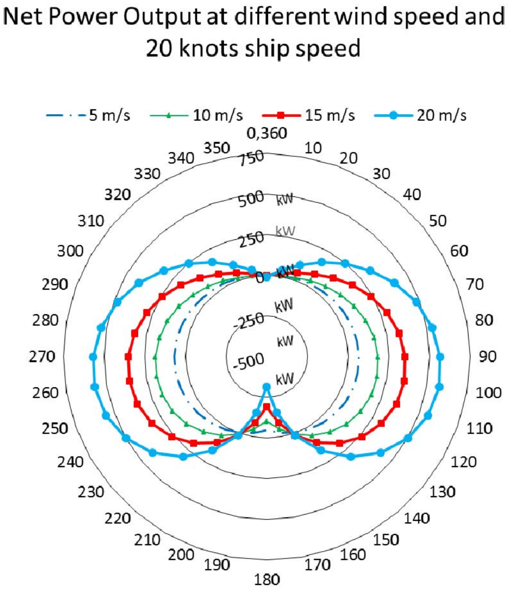


Fig. 6. Effect of Wind Speed variation on power output (kW) over all the true wind angle from 0° to 360° at 20 knots ship speed.

C. *Effect of Coeffient of Rotation(C_{rot}) on Net Power Output(P_{net}):*

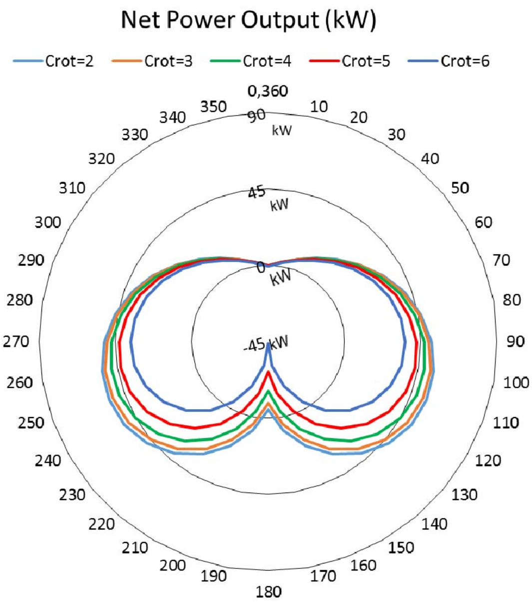


Fig. 7. Effect of Coefficient of rotation on power output (kW) over all true wind angle from 0° to 360° at 15 knots ship speed.

Coefficient of Rotation is the ratio of rotational speed of rotor to apparent wind velocity. In above cases of B and C, C_{rot} is assumed as constant and is equal to 5. When values of C_{rot} is changed the change in net power output is shown in Fig. 7. The net power output variation is calculated for C_{rot} values of 2, 3, 4, 5, 6. The net power output decreases as C_{rot} increases. The calculations have been made for constant values of C_L = 12.5, C_D = 0.2, V_t = 5 m/s and V_s = 15 knots. The value of net power output obtained are given in Table II for three different true wind angles (γ).

TABLE II. NET POWER OUTPUT AT DIFFERENT TRUE WIND ANGLES

	Net Power Output (kW)				
γ (Degree)	**C_{rot}=2**	**C_{rot}=3**	**C_{rot}=4**	**C_{rot}=5**	**C_{rot}=6**
70	40.36	39.48	37.82	35.18	31.34
180	-4.73	-8.58	-15.76	-27.22	-43.87
260	54.18	52.31	48.81	43.23	35.12

D. *Effect of Coeffient of Rotation(C_{rot}) on Power consumption(P_{con}):*

When values of C_{rot} is changed the change in power consumption is shown in Fig. 8. The power consumed is calculated for C_{rot} values of 2, 3, 4, 5, 6. The power consumption increases as C_{rot} increases . The calculations have been made for constant values of C_L = 12.5, C_D = 0.2, V_t = 5 m/s and V_s = 15 knots.

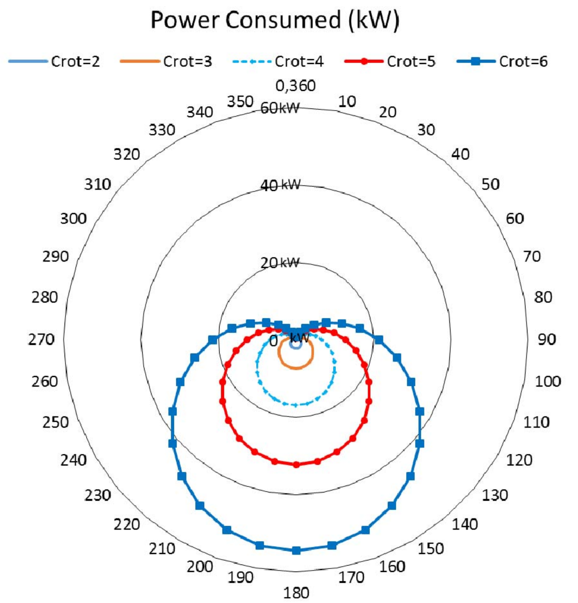


Fig. 8. Effect of Coefficient of rotation on Power consumption (kW) over all true wind angle from 0° to 360° at 15 knots ship speed.

The value of power consumed obtained are given in Table III for three different true wind angles (γ).

TABLE III. POWER CONSUMED BY ROTOR AT DIFFERENT TRUE WIND ANGLES

	Power consumed (kW)				
γ (degree)	**C_{rot}=2**	**C_{rot}=3**	**C_{rot}=4**	**C_{rot}=5**	**C_{rot}=6**
70	0.526	1.70	3.90	7.42	12.54
180	2.31	7.44	17.01	32.29	54.49
260	1.12	3.61	8.27	15.72	26.53

VII. Conclusions

- At ship speed of 15 knots, net power output of the Flettner rotor system increases as the true wind speed increases. The maximum values of net power output are 42.2 kW, 124 kW, 239.9 kW and 386.7 kW at 5 m/s, 10 m/s, 15 m/s, 20 m/s wind speed respectively.
- For increased value of ship speeds, it gives further higher power. At ship speed of 20 knots, the maximum values of net power are 68.2 kW, 189.5 kW, 358.8 kW and 575.2 kW at 5 m/s, 10 m/s, 15 m/s, and 20 m/s wind speed respectively..
- Net power output of flettner rotor decreases as coefficient of rotation increases because the power consumed by rotor increases with the increase in the coefficient of rotation.
- Maximum power consumed is 2.3 kW, 7.44 kW, 17.0 kW, 32.29 kW and 54.49 kW corresponding to the coefficient of rotation values of 2, 3, 4, 5 and 6 respectively. Maximum values of net power generated are 54.62 kW, 52.39 kW, 48.81 kW, 43.23 kW, and 35.96 kW corresponding to the coefficient of rotation values of 2, 3, 4, 5 and 6 respectively.

References

[1]. International Renewable Energy Agency, "Report on Renewable Energy Options for Shipping Technology Brief," Abu Dhabi, United Arab Emirates, January 2015.

[2]. International Maritime Organization, "Third IMO Greenhouse Gas Study 2014," 4 Albert Embankment, London. 2015.

[3]. D. R. Pearson, "The Use of Flettner Rotors in Efficient Ship Design," The Royal Institution of Naval Architects (2014). http://www.bmtdsl.co.uk/media/6097883/BMTDSL%20The%22Use%20Of%20Flettner%20Rotors%20In%20Efficient%20ShiS%20Design%20Conference%20paper%20(RINA%202014).pdf. Downloaded on: 23rd July 2016.

[4]. Wikipedia. (2016, Dec. 25). Flettner ship [online]. Available: https://en.wikipedia.org/wiki/Rotor_ship.

[5]. Deutsches Technikmuseum. (2016, Dec. 25). The Flettner Rotor – An Invention Ahead of Its Time? [online]. Available: http://www.sdtb.de/Flettner-Rotor.1623.0.html.

[6]. A. Thom, "The Effect of Discs on the Air Forces on a Rotating Cylinder", Aeronautical Research Committee Reports and Memoranda No. 1623, His Majesty Stationery Office, London, 1935.

[7]. J. F. Wellicome, "Some Comments on the Relative Merits of Various Wind Propulsion Devices," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 20, pp. 111-142, 1985.

[8]. L. Bergeson, C, Kent Greenwald, "Sail Assist Developments 1979-1985," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 19,pp. 45-114, 1985.

[9]. Dr. Helge Möller, "Ten times better than a conventional cloth sails," University of Flensburg, 2006.

[10]. Nicholas D. Johnson. "High-Reynolds Number Flow Past a Rotating Cylinder with and Without Thom Disc," M.S. Thesis, School of Mechanical, Aerospace and Civil Engineering Faculty of Engineering and Physical Sciences, University of Manchester, 2011.

[11]. Norsepower OY Ltd., 2015. 21th August 2016. [online]. Available: http://www.norsepower.com/rotor-sail solution/Reference%20installation9.

[12]. M. Silvanius, "Wind assisted propulsion for pure car and truck carriers," Master Thesis, KTH Centre for Naval Architecture, January 2009.

[13]. M. Traut, A. Bows, P. Gilbert, S. Mander, P. Stansby, C. Walsh, and R. Wood, "Low C for the High Seas Flettner rotor power contribution on a route Brazil to UK," Second International Workshop on Successful Strategies in Supply Chain Management Template, 2012.

[14]. M. Traut, A. Bows, P. Gilbert, C. Walsh, and R. Wood, "Towards Very Low Carbon Shipping", Available online: https://www.escholar.manchester.ac.uk/api/datastream?publicatipubli=uk-ac-man-scw:221995&datastreamId=FULL-TEXT.PDF. Downloaded on: 23rd July 2016

[15]. P. Kindberg. "Wind-powered auxiliary propulsion in cargo ships," Bachelor's thesis, Department of Environmental engineering, Helsinki Metropolia University, August, 2015.

[16]. T. J. Craft, H. Iacovides, N. Johnson, and B. E. Launder, "Back to the future: Flettner-Thom rotors for maritime propulsion?" Turbulence, Heat and Mass Transfer 7,Begell House, Inc. pp. 1–10, 2012.

[17]. W. S. Janna, Boundary-Layer Flow," in *Introduction to Fluid Mechanics*, CRC Press, New York, 2010, pp. 649-650.

[18]. E-Ship 1: Magnus Sailing (2016, Dec. 25). [online]. Available: http://lshipdesign.blogspot.in/2014/08/magnus-sailing-e-ship-1.html.