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Analysis of Energy Efficiency of Rotate Flettner Rotor Based on Variation in Wind Direction and Rotor's Material

Jürgen Siegl [1], Irfan Syarief Arief [2], Akbar Rizqi Hartawan[3]
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***Abstract*— flettner rotor is a cylindrical object which installed vertically on the ship's body. It rotates on its axis to utilize the airflow from the wind and help the ship to generate additional thrust force by using the principle of magnus effect. This additional thrust force produced by the flettner rotor helps to reduce the fuel consumption which used as an energy source for the main or auxiliary engine. However, the flettner rotor has possibilities to operate in a certain different condition which can affect the efficiency of the flettner rotor usage. The discussion is to find out how much power is needed to rotate a rotor based on the variation of the material being used, how does the wind direction affect the performance of the flettner rotor as an alternative ship propulsion system, how does the energy efficiency get affected by the variation of material and the wind direction. From the discussion of this paper, it is concluded that aluminum is the material that requires the least power to rotate a flettner rotor with 77,2276 kW on the speed of 14.4 rad/s and it gives its maximum contribution when the wind direction towards the flettner rotor is coming through the port side of the ship with the angle of 90 ° and the flettner rotor rotates in clockwise direction. It is also concluded that the best configuration of flettner rotor to produce a good energy efficiency are by using aluminum as the rotor's material, having wind that coming through from the angle of 90°, and the flettner rotor rotates at 14.4 rad/s with apparent wind speed at 7.2 m/s. This configuration can save fuel consumption of the ship up until 570.768 kg on 5000 km voyage.**

Keywords—CFD, energy efficiency, flettner rotor, materials, wind direction

I. INTRODUCTION

The shipping industry is an industry involves a huge, multi-billion of dollars around it. This industry is the lifeblood of the world's economy and it accounts for 90% of the world's trade. Ships are able to carry goods in quantities that are impossible to transport by the other mode of transportations. Cited as the most energy efficient mode of transport, it contains various challenges inside the industry. Currently, the shipping industry contributes for approximately 3% of the total CO2 value in the world and it's expected to increase around 20-25% of global anthropogenic CO2 by 2050 due to growth in international trade and other industry sector decarbonisation effort (Rehmatulla, 2015). This growth in international trade will directly affect the amount of shipping operations to be done in order to fill the needs. However, this activity also mean that there will be an increase in fuel consumption and expenses for the operation. Furthermore, this increasing value of fuel consumption results in increasing value of CO2 produced [1]. This is dangerous to the environment and effects significantly to the human's health. According to a Danish study from 2011, smokestack emissions from international shipping kill approximately 50,000 people a year in Europe, at an annual cost to society of more than €58 billion. These problems cannot be left unsolved and actions must be taken immediately in order to deal with these problems.

Several technologies and regulations have been identified to solve these problems. One of the solutions that might come up to meet this issue is using alternative energy as a source of energy. The alternative energy that has been applied to the shipping industry is the utilization of wind as a source of energy through the media flettner rotor.

Flettner rotor is an object which shaped cylindrical. It installed vertically on the ship's body and rotate on its axis to utilize the airflow from the wind and help the ship to generate additional thrust force by using the principle of magnus effect. This additional thrust force produced by the flettner rotor helps to reduce the fuel consumption which used as an energy source for the main or auxiliary engine. The force itself depends on several parameters that affects the rotor's work such as the wind, the turbine's geometry, the turbine's operational condition, and the ships factor.

The Flettner Rotor is a simple technology that utilizes the working principle of the magnus effect where in its use, the rotor must rotate to produce a difference in pressure which will cause the thrust to emerge. But in fact, to be able to produce an optimal thrust, the flettner rotor is faced with several kinds of conditions that can lead to the fluctuation of efficiency value from the rotor. Several things that can affect the performance efficiency of the flettner rotor are the power needed to rotate the rotor and the direction of the wind. This research paper will focus on calculating the power consumption for the rotor, the influence of wind direction for the rotor, and the performance efficiency of the rotor for its implementation on ship.

To analyse the flettner rotor, Computational Fluid Dynamic or CFD method is often chose to help researchers understand about the rotor work better. CFD is a numerical simulation method and data structures that

Jürgen Siegl, Hochschule Wismar, Rostock, 18119, Germany. E-mail: juergen.siegl@hs-wismar.de
Irfan Syarief Arief, Departement of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia. E-mail: irfansyah@its.ac.id
Akbar Rizqi Hartawan, Departement of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia. E-mail: hartawanakbar@gmail.com

analyse the characteristics that involves fluid flows on a machine that has been designed. Computers are used to calculate the free-stream flow simulation of the fluid and the interaction between the fluid and surfaces defined by boundary condition that has been set. It helps the engineer to simulate a machine or product so it doesn't take time and high cost. In terms of this paper, this method is able to analyse the fluid flow around the rotor and find several parameters desired.

II. Method

A. Ship resistance training

The first step of this paper is to define the ship's that will be used. This paper will use KRISO -KCS ship's model. It is a ship model that provided by the Maxsurf software and it is available to use for everyone. KRISO -KCS ship's model is a ship model with 7,273 meters long in LWL, 0.51 meters wide, and draft in 0.331 meters. Later, it will be scale up to 15 x to use it as a ship's reference for the analysis of flettner rotor energy efficiency. The process of scaling up the ship is done also by using the Maxsurf software that directly attain the information of the ship's main parameter such as its LWL, Beam, Draft, Displaced volume, Wetted area, and etc. These parameters existed later on will be used to calculate the ship's resistance once when the process of scaling up the model has been done.

When the process of scaling up is done, resistance calculation take place. Resistance or ship resistance is defined as a force needed to make a ship move in a constant velocity. There are several methods existed to calculate the resistance such as Guldhammer Harvald, Holtrop, Ayre, and etc. On this paper, the resistance calculation method used is the Holtrop method which is provided by the Maxsurf Resistance software. Now go to the software, select the "Open Design Data" and choose the Ship's data that previously made. Now the ship is ready to be analyzed.

Now choose the analysis on menu tab and select the methods option. Then there will be options shown up on the screen. It shown up various method available to calculate the resistance of ship's design inserted. Check list the "Holtrop" box and "use 19th ITTC modified formula" on screen and then press ok. Then choose desired ship's velocity on analysis and input the ship design speed range. The speed range will be from 12 knots to maximum 15 knots. Finally, the results will be shown in "results window" and give information regarding ship's resistance and engine power for the ship. Based on the result above, it is stated that the resistance value of the ship on 15 knots is 142.7 kN.

B. Flettner Rotor Creation

Now the process of designing Flettner Rotor can begin. In this paper, rotor's parameter such as its dimension, RPM, and the other is referring to the graph Figure 1 created by (A. De Marco, S. Mancini, C. Pensa, R. Scognamiglio, and L. Vitiello). There stated various value of SR, AR, CL, and CD. Each of these values are important and represent several factors to be selected in the process of designing Flettner Rotor.

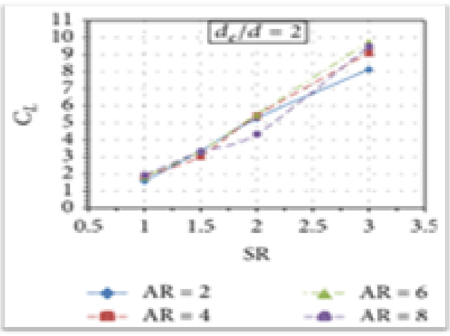

Figure. 1. AR SR CL graph.

1) Aspect Ratio

The AR of Flettner device represents the ratio between height and diameter. Thus, from this ratio the value of rotor's height and diameter can be determined. Based on the graph, the AR value chosen for this paper is 6 and the diameter value is previously to be set on 3 meters. Therefore, the value of rotor's height can be determine using this equation.

$$AR = \frac{H\,(m)}{d\,(m)} \tag{1}$$

2) Spin Ratio

It is another factor that influence the aerodynamic characteristics of a Flettner Rotor. It represents the ratio between the circumferential speed of the rotor and the free stream velocity. Based on the graph, the SR value chosen for this paper is 3 and the value of the wind speed is to be varied from 7.2 meter/second until 2.7 meter/second. Therefore, the value of rotor's RPM can be determined and varied as well. When the AR and SR value are identified, the next parameter to be decided is the end plate.

$$SR = \frac{\Omega\left(\frac{rad}{s}\right) \times d(m)}{2 \times u\,(m)} \tag{2}$$

3) End Plate

Now the parameter to be selected is the End Plate. It has the purpose to optimize its aerodynamic efficiency by using this plate at the top of the cylinder.

$$EP = \frac{de\ (m)}{d\ (m)} \quad (3)$$

4) Lift & Drag Force Calculation

Lift is a force that is perpendicular to the oncoming flow direction. It is created by an object that rotating through a moving fluid resulting in a pressure difference among the body and start to create a lift force. While drag is a force that acts opposite to the relative motion of an object moving with respect to a surrounding fluid. Sometimes it is called as an air resistance or type of friction. These forces will used as a reference for the force that the flettner rotor will produce.

$$CD = \frac{D\ (N)}{0.5 \times \rho\ (kg/m^3) \times A\ (m^2) \times U^2\ (m/s)} \quad (4)$$

$$CL = \frac{L\ (N)}{0.5 \times \rho\ (kg/m^3) \times A\ (m^2) \times U^2\ (m/s)} \quad (5)$$

5) Power Calculation

In this section, the purpose of this calculation is to determine how much power needed to rotate Flettner Rotor and produce forces based on parameters being used.

$$P\ (kW) = \frac{T\ (Nm) \times \Omega\ (RPM)}{5252} \times 0.745 \quad (6)$$

Torque is defined as a force that makes an object to rotate. Just as a linear force is a push or a pull, a torque can be called as a twist to an object.

$$T\ (Nm) = I\ (kgm2) \times \boldsymbol{\alpha}\ (rad/s^2) \quad (7)$$

C. Simulation Process

1) *Pre- Processor*

Consist of the input from a flow problem that will be simulated. Defining domain, fluid properties, and boundary condition is located in this step. The object to be analysed is also going through meshing process in this step.

2) *Processor*

In solver step, include the stage of calculation for every iteration in parts associated with the mesh configuration and the parameters/ method being inputted

3) *Post Processor*

Post processing is an end step process which consist of result from the calculation. Visualization from the formulation is also can be seen in this step with variation of 2 dimension or 3-dimensional view.

D. Wind Direction Variation

The force value is obtained, the force resultant and the direction is obtained as well. Now, the process proceeding to see how the force produce by the flettner is working on the ship moving to the desired direction on various wind angle. This process will be done by using vector lines on Autocad software to determine its effect on the ship. The first thing to do is to prepare the data for the process. Several data needed for this process are ship's resistance, force resultant for each flettner rotor different parameter, force directions, and ship directions.

- Line Definition

The first thing to do is to create lines for each different purpose. Each line represents different value and to make it easy to understand, each line has different colour.

Figure. 2. Line definition.

- Drawing The Line

The next process is to draw the line based on its direction. so the first thing to draw is to draw the ship force line towards x+ direction with dimension of the ship. Then draw the wind direction followed by the force resultant created by the wind direction (based on simulation). Move the resultant force of flettner rotor on the edge of the ship force to determine the resultant created by the flettner rotor and the ship. Draw a line that connect the edge of resultant force of flettner rotor to the zero point. This is a line that represent a resultant force between the flettner rotor and the ship. Snap to Geometry. The purpose of this automatic step is to paper a mesh obtained from previous results on geometric shapes so as to produce a smooth geometric shape.

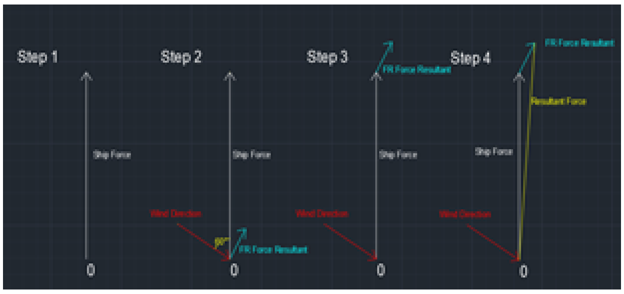

Figure. 3. Drawing the line.

Now repeat the step with variation on the wind direction and the flettner rotor resultant. It creates different value for each different parameter inserted

E. Energy Efficiency Analysis

It will be going to calculate the efficiency energy for the operation of flettner rotor. This calculation will be based on the fuel consumption of main engine and auxiliary engine during a voyage. This calculation will compare the operation of ship with flettner rotor and without flettner rotor.

The first step on this process is to calculate the time taken for a voyage without a flettner rotor. It will be calculated by using the formula:

$$t(hour) = \frac{d\,(km)}{v(km/h)} \tag{8}$$

Now once the time taken is already determined, proceeding to the calculation of main engine and auxiliary engine consumption calculation. For the main engine, it is calculated by using the formula of

$$m(kg) = \frac{t\,(hour)\ \times M/E(kW) \times ME\ SFOC\ (\frac{g}{kWH})}{(1000)} \tag{9}$$

For the auxiliary engine, it is calculated by using the formula of

$$m(kg) = \frac{t\,(hour)\ \times A/E(kW) \times AESFOC\ (\frac{g}{kWH})}{(1000)} \tag{10}$$

For the Flettner Rotor, it is calculated by using the formula of

$$m(kg) = \frac{t\,(hour)\ \times FR\ (kW) \times AESFOC\ (\frac{g}{kWH})}{(1000)} \tag{11}$$

These formulas will be used to compare the operation between ship with flettner rotor and ship without flettner rotor on varied distance.

III. Result and Discussion

1) Ship Resistance Result

The calculation done by using the Maxsurf resistance software. It is based on the selected ship model that has been chosen. The methods used for the calculation is by using the holtrop method and done in several different ship speed.

	Speed (kn)	Froude No. LWL	Froude No. Vol.	Holtrop Resist. (kN)	Holtrop Power (kW)
1	12.000	0.185	0.570	88.5	546.251
2	12.100	0.187	0.575	90.0	560.371
3	12.200	0.188	0.580	91.6	574.758
4	12.300	0.190	0.584	93.1	589.414
5	12.400	0.191	0.589	94.7	604.344
6	12.500	0.193	0.594	96.3	619.552
7	12.600	0.194	0.599	98.0	635.039
8	12.700	0.196	0.603	99.6	650.811
9	12.800	0.197	0.608	101.3	666.871
10	12.900	0.199	0.613	103.0	683.223
11	13.000	0.200	0.618	104.6	699.870
12	13.100	0.202	0.622	106.4	716.817
13	13.200	0.204	0.627	108.1	734.067
14	13.300	0.205	0.632	109.9	751.625
15	13.400	0.207	0.637	111.6	769.495
16	13.500	0.208	0.641	113.4	787.680
17	13.600	0.210	0.646	115.2	806.186
18	13.700	0.211	0.651	117.1	825.016
19	13.800	0.213	0.656	118.9	844.174
20	13.900	0.214	0.660	120.8	863.665
21	14.000	0.216	0.665	122.7	883.491
22	14.100	0.217	0.670	124.6	903.658
23	14.200	0.219	0.675	126.5	924.168
24	14.300	0.221	0.679	128.5	945.025
25	14.400	0.222	0.684	130.4	966.231
26	14.500	0.224	0.689	132.4	987.790
27	14.600	0.225	0.694	134.4	1009.704
28	14.700	0.227	0.698	136.5	1031.975
29	14.800	0.228	0.703	138.5	1054.605
30	14.900	0.230	0.708	140.6	1077.595
31	15.000	0.231	0.713	142.7	1100.948
32	15.100	0.233	0.717	144.8	1124.663

Figure. 4. Resistance result.

2) Flettner Rotor Creation

TABLE 1.
LIFT FORCE RESULT

No	Flux Vel (m/s)	Rotation (rad/s)	Lift (N)
1	7.2	14.4	31912.7
2	6.9	13.8	29308.72
3	6.3	12.6	24433.16
4	5.6	11.2	19305.22
5	4.5	9	12465.9
6	2.7	5.4	4487.724

TABLE 2.
DRAG FORCE RESULT

No	Flux Vel (m/s)	Rotation (rad/s)	Drag (N)
1	7.2	14.4	1866.24
2	6.9	13.8	1788.48
3	6.3	12.6	1632.96
4	5.6	11.2	1451.52
5	4.5	9	1166.4
6	2.7	5.4	699.84

No	Diameter	Material	Density	Mass	Ω Angular Velocity		Time	α Angular Acc.	I(Inertia Moment)	T(Torque)	Power Rotor Consumption
	(meter)		(kg/m3)	(kg)	(rad/s)	(RPM)	(secon)	(rad/s2)	(kg/m2)	(Nm)	(kW)
1	3	S. Steel	8000	3617.31	14.4	137.508	10	1.44	8138.93625	11720.1	228.8226685
2	3	S. Steel	8000	3617.31	13.8	131.779	10	1.38	8138.93625	11231.7	210.1513744
3	3	S. Steel	8000	3617.31	12.6	120.32	10	1.26	8138.93625	10255.1	175.1923556
4	3	S. Steel	8000	3617.31	11.2	106.951	10	1.12	8138.93625	9115.61	138.4235896
5	3	S. Steel	8000	3617.31	9	85.9428	10	0.9	8138.93625	7325.04	89.38385489
6	3	S. Steel	8000	3617.31	5.4	51.5657	10	0.54	8138.93625	4395.03	32.17818776
7	3	Alumunium	2700	1220.84	14.4	137.508	10	1.44	2746.89	3955.52	77.22762295
8	3	Alumunium	2700	1220.84	13.8	131.779	10	1.38	2746.89	3790.71	70.92606344
9	3	Alumunium	2700	1220.84	12.6	120.32	10	1.26	2746.89	3461.08	59.12739882
10	3	Alumunium	2700	1220.84	11.2	106.951	10	1.12	2746.89	3076.52	46.71794475
11	3	Alumunium	2700	1220.84	9	85.9428	10	0.9	2746.89	2472.2	30.16704022
12	3	Alumunium	2700	1220.84	5.4	51.5657	10	0.54	2746.89	1483.32	10.86013448
13	3	Steel	7850	3549.48	14.4	137.508	10	1.44	7986.33225	11500.3	224.5322731
14	3	Steel	7850	3549.48	13.8	131.779	10	1.38	7986.33225	11021.1	206.2110634
15	3	Steel	7850	3549.48	12.6	120.32	10	1.26	7986.33225	10062.8	171.9075216
16	3	Steel	7850	3549.48	11.2	106.951	10	1.12	7986.33225	8944.69	135.8281652
17	3	Steel	7850	3549.48	9	85.9428	10	0.9	7986.33225	7187.7	87.70791919
18	3	Steel	7850	3549.48	5.4	51.5657	10	0.54	7986.33225	4312.62	31.57485091
19	3	Zinc	7000	3165.14	14.4	137.508	10	1.44	7121.5695	10255.1	200.2198429
20	3	Zinc	7000	3165.14	13.8	131.779	10	1.38	7121.5695	9827.77	183.8824599
21	3	Zinc	7000	3165.14	12.6	120.32	10	1.26	7121.5695	8973.18	153.2933172
22	3	Zinc	7000	3165.14	11.2	106.951	10	1.12	7121.5695	7976.16	121.1206457
23	3	Zinc	7000	3165.14	9	85.9428	10	0.9	7121.5695	6409.41	78.21087612
24	3	Zinc	7000	3165.14	5.4	51.5657	10	0.54	7121.5695	3845.65	28.1559154

Figure. 5. Flettner rotor variation.

The Flettner rotor creation process done in several variation. It varies in the value of density of material, wind speed, and rotation speed. Now the result of the calculation indicates that the higher density of the material used the higher power needs to rotate the flettner rotor. It can also be seen that different wind speed that attacks flettner rotor produce different force as the higher the wind speeds the more force produced by the flettner rotor. this paper, rotor's parameter such as its dimension, RPM, and the other is referring to the graph Figure 1 created by (A. De Marco, S. Mancini, C. Pensa, R. Scognamiglio, and L. Vitiello). There stated various value of SR, AR, CL, and CD. Each of these values are important and represent several factors to be selected in the process of designing Flettner Rotor.

3) Simulation Result

This is the most important stage as the force produced by the simulation will be used for later wind direction & energy efficiency analysis. Based on the simulation, the flettner rotor produce such amount of lift and drag force that the result is not too far with the calculation by using an equation.

Force Based on Simulation						
Rotation (rad/s)	Wind Speed (m/s)	Force X (N)	Force Y (N)	Force Resultant (N)	Cos	Direction From Y
14.4	7.2	-1219.6848	26901.3582	26928.99371	0.999848	0.998973763
13.8	6.9	-1184.6111	25025.3936	25053.41547	0.999848	0.998881514
12.6	6.3	-976.24295	20491.3572	20514.59899	0.999848	0.998867063
11.2	5.6	-775.41935	16209.0434	16227.58036	0.999848	0.99885769
9	4.5	-501.21541	10450.6943	10462.70656	0.999848	0.998851899
5.4	2.7	-182.34852	3756.01251	3760.436269	0.9998481	0.998823604

Figure. 6. Flettner rotor simulation result.

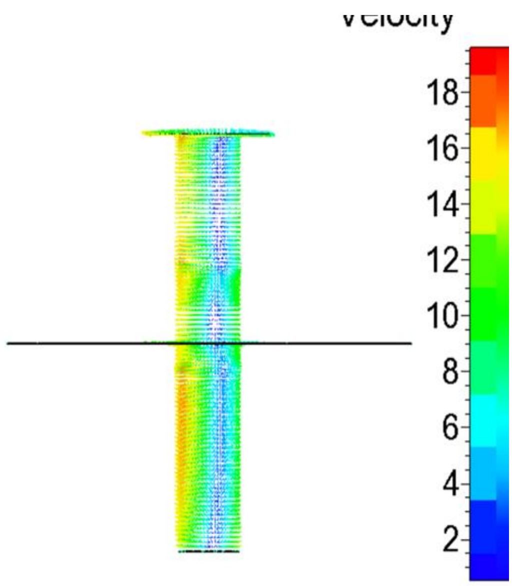

Figure. 7. Flettner rotor simulation visual result.

Based on the simulation result, the flettner rotor produce a lift force towards the Y+ direction and a drag force towards the X- direction. On the visual side, the red area indicates a high velocity area which creates pressure drop on the faces while on the other side it increases the value of pressure. This differences make a lift from the high pressure area towards the low pressure area (Y- towards Y+).

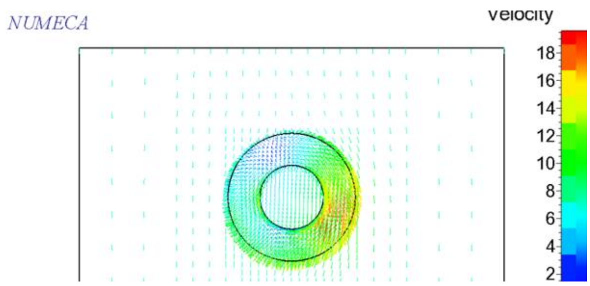

Figure. 8. Flettner Rotor 7.2m/s at 14.4 rad/s.

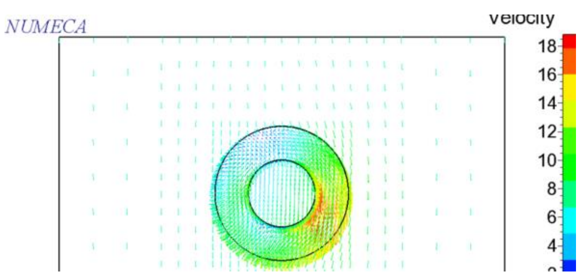

Figure. 9. Flettner Rotor 6.9m/s at 13.8 rad/s.

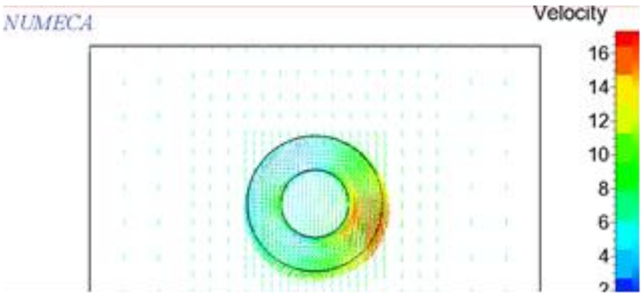

Figure. 10. Flettner Rotor 6.3m/s at 12.6 rad/s .

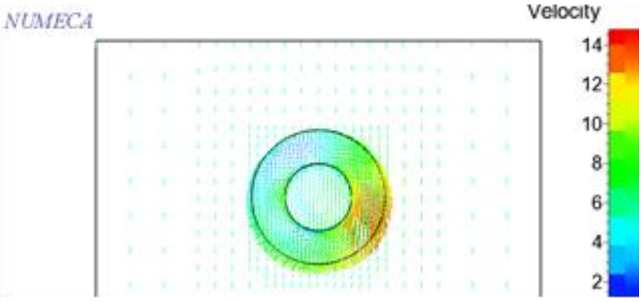

Figure. 11. Flettner Rotor 5.6m/s at 11.2rad/s.

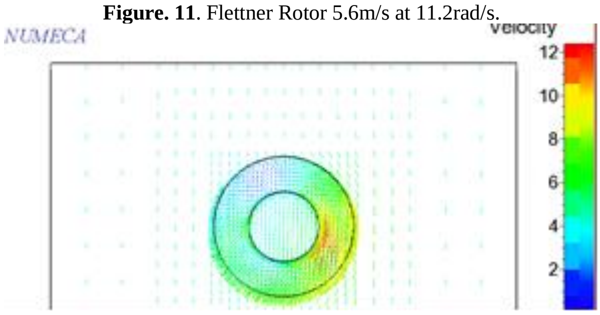

Figure. 12. Flettner Rotor 4.5m/s at 9rad/s.

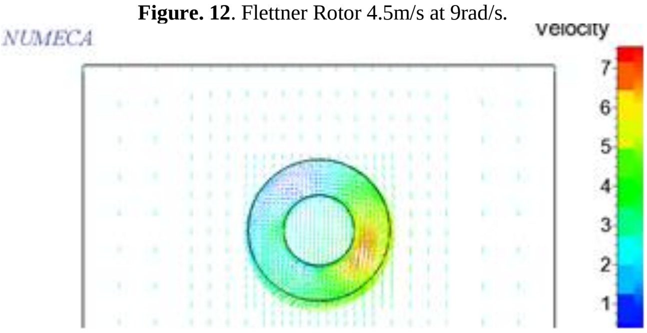

Figure. 13. Flettner Rotor 2.7m/s at 4.5 rad/s.

4) Wind Direction Analysis

The force value is obtained, the force resultant and the direction is obtained as well. Now, the process proceeding to see how the force produce by the flettner is working on the ship moving to the desired direction on various wind angle. This process will be done by using vector lines on Autocad software to determine its effect on the ship. The first thing to do is to prepare the data for the process. Several data needed for this process are ship's resistance, force resultant for each flettner rotor different parameter, force directions, and ship directions.

Starboard Side							
Wind Speed	Ship Speed	Direction (Degree)	Ship Resis	Force Resultan	Result	Speed After	Direction
m/s	Knot	°	N	N	N	kn	°
7.2	15	0	142700	26928.99371	144756	15.1	11
7.2	15	15	142700	26928.99371	1377416	14.765	11
7.2	15	30	142700	26928.99371	130863	14.422	10
7.2	15	45	142700	26928.99371	124748	14.108	9
7.2	15	60	142700	26928.99371	119843	13.85	6
7.2	15	75	142700	26928.99371	116747	13.68	3
7.2	15	90	142700	26928.99371	115776	13.638	0
7.2	15	105	142700	26928.99371	117044	13.69	4
7.2	15	120	142700	26928.99371	120410	13.86	7
7.2	15	135	142700	26928.99371	125504	14.153	9
7.2	15	150	142700	26928.99371	131762	14.475	10
7.2	15	165	142700	26928.99371	138641	14.81	11
7.2	15	180	142700	26928.99371	145669	15.15	11
6.9	15	0	142700	25053.41547	144416	15.087	10
6.9	15	15	142700	25053.41547	137923	14.765	10
6.9	15	30	142700	25053.41547	131561	14.46	9
6.9	15	45	142700	25053.41547	125896	14.165	8
6.9	15	60	142700	25053.41547	121397	13.928	6
6.9	15	75	142700	25053.41547	118543	13.78	3
6.9	15	90	142700	25053.41547	117651	13.73	0
6.9	15	105	142700	25053.41547	118829	13.79	3
6.9	15	120	142700	25053.41547	121929	13.96	6
6.9	15	135	142700	25053.41547	126592	14.205	8
6.9	15	150	142700	25053.41547	132370	14.49	10
6.9	15	165	142700	25053.41547	138810	14.815	10
6.9	15	180	142700	25053.41547	145302	15.125	10
6.3	15	0	142700	20514.59899	143821	15.06	8
6.3	15	15	142700	20514.59899	138466	14.799	8
6.3	15	30	142700	20514.59899	133309	14.548	8
6.3	15	45	142700	20514.59899	128744	14.311	6
6.3	15	60	142700	20514.59899	125163	14.128	5
6.3	15	75	142700	20514.59899	122902	14.013	2
6.3	15	90	142700	20514.59899	122198	13.966	0
6.3	15	105	142700	20514.59899	123110	14.016	3
6.3	15	120	142700	20514.59899	125560	14.164	5
6.3	15	135	142700	20514.59899	129303	14.33	7
6.3	15	150	142700	20514.59899	133969	14.575	8
6.3	15	165	142700	20514.59899	139185	14.829	8
6.3	15	180	142700	20514.59899	144538	15.087	8

Figure. 14. Wind Direction from Starboard side.

Port Side							
Wind Speed	Ship Speed	Direction (Degree)	Ship Resis	Force Resultan	Result	Speed After	Direction
m/s	Knot	°	N	N	N	kn	°
7.2	15	0	142700	26928.99371	144756	15.1	11
7.2	15	15	142700	26928.99371	151493	15.42	10
7.2	15	30	142700	26928.99371	157725	15.7	9
7.2	15	45	142700	26928.99371	162565	15.925	7
7.2	15	60	142700	26928.99371	166400	16.1	5
7.2	15	75	142700	26928.99371	168757	16.2	3
7.2	15	90	142700	26928.99371	169624	16.224	0
7.2	15	105	142700	26928.99371	168955	16.18	2
7.2	15	120	142700	26928.99371	166763	16.1	4
7.2	15	135	142700	26928.99371	163136	15.939	7
7.2	15	150	142700	26928.99371	158251	15.75	8
7.2	15	165	142700	26928.99371	152345	15.45	10
7.2	15	180	142700	26928.99371	145678	15.15	11
6.9	15	0	142700	25053.41547	144461	15.087	10
6.9	15	15	142700	25053.41547	150743	15.375	9
6.9	15	30	142700	25053.41547	156396	15.637	8
6.9	15	45	142700	25053.41547	161115	15.84	6
6.9	15	60	142700	25053.41547	164668	15.991	4
6.9	15	75	142700	25053.41547	166910	16.1	2
6.9	15	90	142700	25053.41547	167741	16.13	0
6.9	15	105	142700	25053.41547	167112	16.12	2
6.9	15	120	142700	25053.41547	166059	16.06	4
6.9	15	135	142700	25053.41547	161672	15.85	6
6.9	15	150	142700	25053.41547	157066	15.645	8
6.9	15	165	142700	25053.41547	151530	15.413	9
6.9	15	180	142700	25053.41547	145329	15.12	10
6.3	15	0	142700	20514.59899	143821	15.06	8
6.3	15	15	142700	20514.59899	149008	15.296	8
6.3	15	30	142700	20514.59899	153696	15.51	7
6.3	15	45	142700	20514.59899	157624	15.68	5
6.3	15	60	142700	20514.59899	160632	15.825	4
6.3	15	75	142700	20514.59899	162517	15.91	2
6.3	15	90	142700	20514.59899	163211	15.93	0
6.3	15	105	142700	20514.59899	162684	15.915	2
6.3	15	120	142700	20514.59899	160949	15.83	4
6.3	15	135	142700	20514.59899	158111	15.71	5
6.3	15	150	142700	20514.59899	154270	15.53	7
6.3	15	165	142700	20514.59899	149675	15.328	8
6.3	15	180	142700	20514.59899	144538	15.087	8

Figure. 15. Wind Direction from Port side.

Based on the table above, the best wind direction for the flettner rotor on this paper is at 90° from the port side, producing the biggest resultant force which resulting in the rising of ship's speed.

5) Energy Efficiency Analysis

On this stage, the energy efficiency analysis is conduct by comparing the fuel consumption of ship with flettner rotor and fuel consumption of ship without flettner rotor.

Using Flettner Rotor														
No	Material	Rotation	Wind Speed	Wind Direction	Force Produced	Ship Speed	Speed w/Flet	FR Power	Distance	Time	/E Oil Con	A/E Oil Cons	FR Cons	Total	Savings
		(rad/s)	(m/s)	°	N	(knots)	(knots)	(kW)	(km)	(hour)	kg	kg	kg	kg	kg
1	S. Steel	14.4	7.2	90	26928.99371	15	16.224	228.823	5000	166.407	36043.7	6543.7812	8605.549	51193	-5130.4
2	S. Steel	13.8	6.9	90	25053.41547	15	16.13	210.151	5000	167.377	36253.8	6581.9161	7949.418	50785.1	-4722.5
3	S. Steel	12.6	6.3	90	20514.59899	15	15.93	175.192	5000	169.478	36708.9	6664.5516	6710.221	50083.7	-4021.1
4	S. Steel	11.2	5.6	90	16227.58036	15	15.75	138.424	5000	171.415	37128.5	6740.7179	5362.496	49231.7	-3169
5	S. Steel	9	4.5	90	10462.70656	15	15.488	89.3839	5000	174.315	37756.5	6854.746	3521.285	48132.6	-2069.9
6	S. Steel	5.4	2.7	90	3760.436269	15	15.175	32.1782	5000	177.91	38535.3	6996.1322	1293.81	46825.2	-762.61
7	Alumunium	14.4	7.2	90	26928.99371	15	16.224	77.2276	5000	166.407	36043.7	6543.7812	2904.372	45491.9	570.768
8	Alumunium	13.8	6.9	90	25053.41547	15	16.13	70.9261	5000	167.377	36253.8	6581.9161	2682.928	45518.6	544.027
9	Alumunium	12.6	6.3	90	20514.59899	15	15.93	59.1274	5000	169.478	36708.9	6664.5516	2264.699	45638.2	424.457
10	Alumunium	11.2	5.6	90	16227.58036	15	15.75	46.7179	5000	171.415	37128.5	6740.7179	1809.842	45679	383.617
11	Alumunium	9	4.5	90	10462.70656	15	15.488	30.167	5000	174.315	37756.5	6854.746	1188.433	45799.7	262.92
12	Alumunium	5.4	2.7	90	3760.436269	15	15.175	10.8601	5000	177.91	38535.3	6996.1322	436.6606	45968.1	94.5395
13	Steel	14.4	7.2	90	26928.99371	15	16.224	224.532	5000	166.407	36043.7	6543.7812	8444.196	51031.7	-4969.1
14	Steel	13.8	6.9	90	25053.41547	15	16.13	206.211	5000	167.377	36253.8	6581.9161	7800.367	50636	-4573.4
15	Steel	12.6	6.3	90	20514.59899	15	15.93	171.908	5000	169.478	36708.9	6664.5516	6584.405	49957.9	-3895.2
16	Steel	11.2	5.6	90	16227.58036	15	15.75	135.828	5000	171.415	37128.5	6740.7179	5261.95	49131.1	-3068.5
17	Steel	9	4.5	90	10462.70656	15	15.488	87.7079	5000	174.315	37756.5	6854.746	3455.262	48066.5	-2003.9
18	Steel	5.4	2.7	90	3760.436269	15	15.175	31.5749	5000	177.91	38535.3	6996.1322	1269.551	46801	-738.35
19	Zinc	14.4	7.2	90	26928.99371	15	16.224	200.22	5000	166.407	36043.7	6543.7812	7529.855	50117.4	-4054.7
20	Zinc	13.8	6.9	90	25053.41547	15	16.13	183.882	5000	167.377	36253.8	6581.9161	6955.741	49791.4	-3728.8
21	Zinc	12.6	6.3	90	20514.59899	15	15.93	153.293	5000	169.478	36708.9	6664.5516	5871.444	49244.9	-3182.3
22	Zinc	11.2	5.6	90	16227.58036	15	15.75	121.121	5000	171.415	37128.5	6740.7179	4692.184	48561.4	-2498.7
23	Zinc	9	4.5	90	10462.70656	15	15.488	78.2109	5000	174.315	37756.5	6854.746	3081.125	47692.4	-1629.8
24	Zinc	5.4	2.7	90	3760.436269	15	15.175	28.1559	5000	177.91	38535.3	6996.1322	1132.083	46663.5	-600.88

Figure. 16. Fuel savings for 5000 km voyage with FR.

Using Flettner Rotor														
No	Material	Rotation	Wind Speed	Wind Direction	Force Produced	Ship Speed	Speed w/Flet	FR Power	Distance	Time	/E Oil Con	A/E Oil Cons	FR Cons	Total	Savings
		(rad/s)	(m/s)	°	N	(knots)	(knots)	(kW)	(km)	(hour)	kg	kg	kg	kg	kg
1	S. Steel	14.4	7.2	90	26928.99371	15	16.224	228.823	2500	83.2034	18021.9	3271.8906	4302.774	25596.5	-2565.2
2	S. Steel	13.8	6.9	90	25053.41547	15	16.13	210.151	2500	83.6883	18126.9	3290.9581	3974.709	25392.5	-2361.2
3	S. Steel	12.6	6.3	90	20514.59899	15	15.93	175.192	2500	84.739	18354.5	3332.2758	3355.111	25041.9	-2010.5
4	S. Steel	11.2	5.6	90	16227.58036	15	15.75	138.424	2500	85.7074	18564.2	3370.3589	2681.248	24615.8	-1584.5
5	S. Steel	9	4.5	90	10462.70656	15	15.488	89.3839	2500	87.1573	18878.3	3427.373	1760.643	24066.3	-1035
6	S. Steel	5.4	2.7	90	3760.436269	15	15.175	32.1782	2500	88.955	19267.7	3498.0661	646.9048	23412.6	-381.3
7	Alumunium	14.4	7.2	90	26928.99371	15	16.224	77.2276	2500	83.2034	18021.9	3271.8906	1452.186	22745.9	285.384
8	Alumunium	13.8	6.9	90	25053.41547	15	16.13	70.9261	2500	83.6883	18126.9	3290.9581	1341.464	22759.3	272.014
9	Alumunium	12.6	6.3	90	20514.59899	15	15.93	59.1274	2500	84.739	18354.5	3332.2758	1132.349	22819.1	212.228
10	Alumunium	11.2	5.6	90	16227.58036	15	15.75	46.7179	2500	85.7074	18564.2	3370.3589	904.9209	22839.5	191.808
11	Alumunium	9	4.5	90	10462.70656	15	15.488	30.167	2500	87.1573	18878.3	3427.373	594.2167	22899.9	131.46
12	Alumunium	5.4	2.7	90	3760.436269	15	15.175	10.8601	2500	88.955	19267.7	3498.0661	218.3303	22984	47.2698
13	Steel	14.4	7.2	90	26928.99371	15	16.224	224.532	2500	83.2034	18021.9	3271.8906	4222.098	25515.8	-2484.5
14	Steel	13.8	6.9	90	25053.41547	15	16.13	206.211	2500	83.6883	18126.9	3290.9581	3900.184	25318	-2286.7
15	Steel	12.6	6.3	90	20514.59899	15	15.93	171.908	2500	84.739	18354.5	3332.2758	3292.203	24978.9	-1947.6
16	Steel	11.2	5.6	90	16227.58036	15	15.75	135.828	2500	85.7074	18564.2	3370.3589	2630.975	24565.6	-1534.2
17	Steel	9	4.5	90	10462.70656	15	15.488	87.7079	2500	87.1573	18878.3	3427.373	1727.631	24033.3	-1002
18	Steel	5.4	2.7	90	3760.436269	15	15.175	31.5749	2500	88.955	19267.7	3498.0661	634.7754	23400.5	-369.18
19	Zinc	14.4	7.2	90	26928.99371	15	16.224	200.22	2500	83.2034	18021.9	3271.8906	3764.928	25058.7	-2027.4
20	Zinc	13.8	6.9	90	25053.41547	15	16.13	183.882	2500	83.6883	18126.9	3290.9581	3477.87	24895.7	-1864.4
21	Zinc	12.6	6.3	90	20514.59899	15	15.93	153.293	2500	84.739	18354.5	3332.2758	2935.722	24622.5	-1591.1
22	Zinc	11.2	5.6	90	16227.58036	15	15.75	121.121	2500	85.7074	18564.2	3370.3589	2346.092	24280.7	-1249.4
23	Zinc	9	4.5	90	10462.70656	15	15.488	78.2109	2500	87.1573	18878.3	3427.373	1540.562	23846.2	-814.89
24	Zinc	5.4	2.7	90	3760.436269	15	15.175	28.1559	2500	88.955	19267.7	3498.0661	566.0417	23331.8	-300.44

Figure. 17. Fuel savings for 2500 km voyage with FR.

Using Flettner Rotor														
No	Material	Rotation	Wind Speed	Wind Direction	Force Produced	Ship Speed	Speed w/Flet	FR Power	Distance	Time	/E Oil Con	A/E Oil Cons	FR Cons	Total	Savings
		(rad/s)	(m/s)	°	N	(knots)	(knots)	(kW)	(km)	(hour)	kg	kg	kg	kg	kg
1	S. Steel	14.4	7.2	90	26928.99371	15	16.224	228.823	1000	33.2814	7208.74	1308.7562	1721.11	10238.6	-1026.1
2	S. Steel	13.8	6.9	90	25053.41547	15	16.13	210.151	1000	33.4753	7250.75	1316.3832	1589.884	10157	-944.49
3	S. Steel	12.6	6.3	90	20514.59899	15	15.93	175.192	1000	33.8956	7341.79	1332.9103	1342.044	10016.7	-804.21
4	S. Steel	11.2	5.6	90	16227.58036	15	15.75	138.424	1000	34.283	7425.69	1348.1436	1072.499	9846.33	-633.81
5	S. Steel	9	4.5	90	10462.70656	15	15.488	89.3839	1000	34.8629	7551.31	1370.9492	704.257	9626.51	-413.99
6	S. Steel	5.4	2.7	90	3760.436269	15	15.175	32.1782	1000	35.582	7707.06	1399.2264	258.7619	9365.05	-152.52
7	Alumunium	14.4	7.2	90	26928.99371	15	16.224	77.2276	1000	33.2814	7208.74	1308.7562	580.8743	9098.37	114.154
8	Alumunium	13.8	6.9	90	25053.41547	15	16.13	70.9261	1000	33.4753	7250.75	1316.3832	536.5855	9103.72	108.805
9	Alumunium	12.6	6.3	90	20514.59899	15	15.93	59.1274	1000	33.8956	7341.79	1332.9103	452.9398	9127.64	84.8914
10	Alumunium	11.2	5.6	90	16227.58036	15	15.75	46.7179	1000	34.283	7425.69	1348.1436	361.9684	9135.8	76.7234
11	Alumunium	9	4.5	90	10462.70656	15	15.488	30.167	1000	34.8629	7551.31	1370.9492	237.6867	9159.94	52.5841
12	Alumunium	5.4	2.7	90	3760.436269	15	15.175	10.8601	1000	35.582	7707.06	1399.2264	87.33211	9193.62	18.9079
13	Steel	14.4	7.2	90	26928.99371	15	16.224	224.532	1000	33.2814	7208.74	1308.7562	1688.839	10206.3	-993.81
14	Steel	13.8	6.9	90	25053.41547	15	16.13	206.211	1000	33.4753	7250.75	1316.3832	1560.073	10127.2	-914.68
15	Steel	12.6	6.3	90	20514.59899	15	15.93	171.908	1000	33.8956	7341.79	1332.9103	1316.881	9991.58	-779.05
16	Steel	11.2	5.6	90	16227.58036	15	15.75	135.828	1000	34.283	7425.69	1348.1436	1052.39	9826.23	-613.7
17	Steel	9	4.5	90	10462.70656	15	15.488	87.7079	1000	34.8629	7551.31	1370.9492	691.0523	9613.31	-400.78
18	Steel	5.4	2.7	90	3760.436269	15	15.175	31.5749	1000	35.582	7707.06	1399.2264	253.9102	9360.2	-147.67
19	Zinc	14.4	7.2	90	26928.99371	15	16.224	200.22	1000	33.2814	7208.74	1308.7562	1505.971	10023.5	-810.94
20	Zinc	13.8	6.9	90	25053.41547	15	16.13	183.882	1000	33.4753	7250.75	1316.3832	1391.148	9958.28	-745.76
21	Zinc	12.6	6.3	90	20514.59899	15	15.93	153.293	1000	33.8956	7341.79	1332.9103	1174.289	9848.98	-636.46
22	Zinc	11.2	5.6	90	16227.58036	15	15.75	121.121	1000	34.283	7425.69	1348.1436	938.4369	9712.27	-499.75
23	Zinc	9	4.5	90	10462.70656	15	15.488	78.2109	1000	34.8629	7551.31	1370.9492	616.2249	9538.48	-325.95
24	Zinc	5.4	2.7	90	3760.436269	15	15.175	28.1559	1000	35.582	7707.06	1399.2264	226.4167	9332.7	-120.18

Figure. 18. Fuel savings for 1000 km voyage with FR.

It turns out that the flettner rotor using alumunium as a material can saved up to 570.768 kg on 5000 km voyage and in 2500 km voyage, it can save up until 285.34 kg of fuel. While in 1000 km voyage, it can save 114 kg of fuel.

IV. CONCLUSION

Based on the result of simulation, calculation, and the analysis of flettner rotor on this paper, it can be concluded that:

1) Aluminum is the material that requires the least power to rotate the flettner rotor with 77.2276 kW power, on the speed of 14.4 rad/s and

10.881 kW power on the rotation speed of 5.4 rad/s.

2) Flettner Rotor gives its maximum contribution when wind direction towards the flettner rotor is coming through the port side of the ship with the angle of 90°. Meanwhile, if the wind direction towards the rotor is coming from the starboard side, it slows up the movement of the ship. These things depend on the direction of rotor's rotational movement whether it is counter- clockwise or not.

3) The best configuration of flettner rotor to produce a good energy efficiency on this paper are by using aluminum as the rotor's material, having wind that coming through from the angle of 90°, and the flettner rotor rotates at 14.4 rad/s with apparent wind speed at 7.2 m/s. This configuration can save fuel consumption of the ship up until 570.768 kg on 5000 km distance.

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