BACHELOR THESIS & COLLOQUIUM – ME184841

ANALYSIS OF ENERGY EFFICIENCY TO ROTATE FLETTNER ROTOR BASED ON VARIATION IN WIND DIRECTION AND ROTOR'S MATERIAL

AKBAR RIZQI HARTAWAN
NRP. 04211541000037

SUPERVISOR :
Prof. Dr.-Ing. Jürgen Siegl
Irfan Syarief Arief, S.T., M.T.

DOUBLE DEGREE PROGRAM
DEPARTMENT OF MARINE ENGINEERING
FACULTY OF MARINE TECHNOLOGY
INSTITUT TEKNOLOGI SEPULUH NOPEMBER
SURABAYA
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APROVAL SHEET

ANALYSIS OF ENERGY EFFICIENCY TO ROTATE FLETTNER ROTOR BASED ON VARIATION IN WIND DIRECTION AND ROTOR'S MATERIAL

BACHELOR THESIS

Submitted to Comply One of The Requirements to Acquire a Bachelor of Engineering Degree in Double Degree of Marine Engineering Program
Department of Marine Engineering - Faculty of Marine Technology
Institut Teknologi Sepuluh Nopember
Department of Marine Studies
Hochschule Wismar, University of Applied Sciences

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SURABAYA
JULI, 2019

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APPROVAL FORM

ANALYSIS OF ENERGY EFFICIENCY TO ROTATE FLETTNER ROTOR BASED ON VARIATION IN WIND DIRECTION AND ROTOR'S MATERIAL

BACHELOR THESIS

Submitted to Comply One of the Requirements to Obtain Bachelor Engineering Degree

on

Bachelor Program Department of Marine Engineering
Faculty of Marine Technology
Institut Teknologi Sepuluh Nopermber

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DECLARATION OF HONOR

With signed below, I declare that:

This thesis has been written and developed independently without any plagiarism act. All contents and ideas drawn directly from internal and external sources are indicated such as cited sources, literatures, and other professional sources.

Student Name	: Akbar Rizqi Hartawan
Student ID Number	: 0421154100037
Thesis Title	: Analysis of Energy Efficiency to Rotate Flettner Rotor Based on Variation in Wind Direction and Rotor's Material
Department	: Double Degree Marine Engineering Program Faculty of Marine Engineering Institut Teknologi Sepuluh Nopember

Surabaya, July 22, 2019

Akbar Rizqi Hartawan

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

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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 bachelor thesis, 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: Flettner Rotor, Energy Efficiency, Materials, Wind Direction, CFD

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Analisa Kinerja dari Shell and Tube Sebagai Pemanas Bahan Bakar Pada Biodiesel

Nama Mahasiswa	**: Akbar Rizqi Hartawan**
NRP	**: 04211541000037**
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Abstrak

Flettner rotor adalah objek silindris yang dipasang secara vertikal di badan kapal. Ia berputar pada sumbunya untuk memanfaatkan aliran udara dari angin dan membantu kapal untuk menghasilkan gaya dorong tambahan dengan menggunakan prinsip efek magnus. Gaya dorong tambahan yang dihasilkan oleh flettner rotor ini membantu mengurangi konsumsi bahan bakar yang digunakan sebagai sumber energi untuk mesin utama atau tambahan. Namun, flettner rotor memiliki kemungkinan untuk beroperasi dalam beberapa kondisi berbeda yang dapat mempengaruhi efisiensi penggunaan flettner rotor. Diantaranya, pembahasan di dalam tesis sarjana ini adalah untuk mengetahui seberapa besar daya yang diperlukan untuk memutar rotor berdasarkan variasi bahan yang digunakan, bagaimana arah angin mempengaruhi kinerja flettner rotor sebagai sistem propulsi kapal alternatif, bagaimana hasi daril efisiensi energi yang dipengaruhi oleh variasi material dan arah angin. Dari pembahasan tesis sarjana ini, disimpulkan bahwa aluminium adalah bahan yang membutuhkan daya paling kecil untuk memutar rotor flettner dengan 77.276 kW pada kecepatan 14,4 rad / s dan memberikan kontribusi maksimum ketika arah angin menuju rotor flettner akan datang melalui sisi port kapal dengan sudut 90 ° dan rotor flettner berputar searah jarum jam. Juga disimpulkan bahwa konfigurasi terbaik bagi flettner rotor agar menghasilkan efisiensi energi yang baik adalah dengan menggunakan aluminium sebagai bahan rotor, memiliki angin yang datang dari sudut 90 °, dan flettner rotor berputar pada 14,4 rad / s dengan kecepatan angin pada 7.2 m / s. Konfigurasi ini dapat menghemat konsumsi bahan bakar kapal hingga 570.768 kg pada perjalanan 5000 km.

Kata Kunci: Flettner Rotor, Efisiensi Energi, Material, Arah Angin, CFD

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PREFACE

First of all, praise to Allah SWT for His grace, mercy, and guidance, the writer is able to completed this final assignment in a timely and smooth manner entitled " Analysis Of Energy Efficiency To Rotate Flettner Rotor Based On Variation In Wind Direction and Rotor's Material".

This thesis is made to attain Double Degree Bachelor of Marine Engineering from Faculty of Marine Technology of Hochschule Wismar and Institut Teknologi Sepuluh Nopember Surabaya.

During my time on completing the thesis, there are many people who support and assist me. Therefore, I would like to dedicate my gratefulness to these names below:

1. Prof. Jürgen Siegl and Mr. Irfan Syarif Arief as my first and second supervisor who guided me through all this process of doing and completing my Bachelor Thesis.
2. My mother, my father, all my families who always have my back and supported me through the ups and downs during the process of doing my Bachelor Thesis.
3. Fadil, Kemal, Hafid, Kitto, Rifram, Bisma, Bagos, Ghara, Ilham who had been by my side and always make me laugh during my sad time.
4. Salsa, Amel, Sonia, Rachell, Putu, Okta, Hadyan, my"Podomoro" who accompany me during my colleague time
5. All Salvage 2015 friends, who had struggle together to attain this Bachelor Degree

Hopefully, this Bachelor Thesis can provide information and able to be useful to any future studies in engineering. I realized this Bachelor Thesis is far from perfect and any corrections and feedbacks will be very welcomed, The author can be reach at hartawanakbar@gmail.com.

Surabaya, July 2019

Author

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CHAPTER I
INTRODUCTION

1.1 Background

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

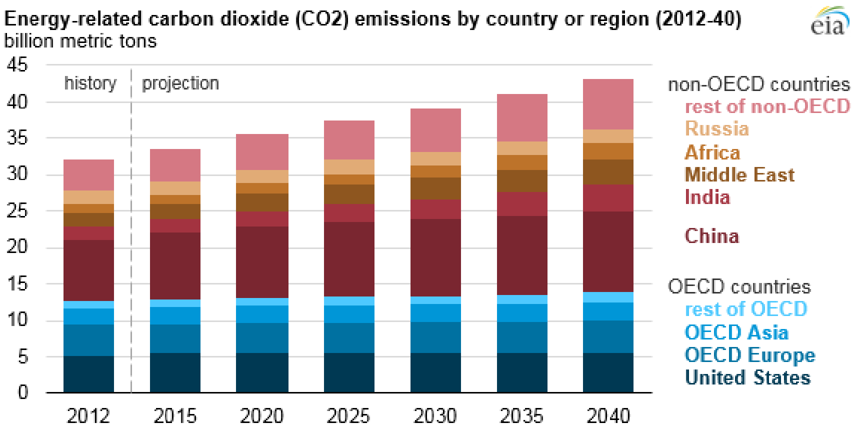

Figure 1. CO2 Emission 2012-2040

Source : U.S. Energy Information Administration, International Energy Outlook 2016

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 means 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 problem

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 analyze the flettner rotor, Computation 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 analyze 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 project, this method is able to analyze the fluid flow around the rotor and find several parameters desired.

1.2 Research Problems

Based on background mentioned above, it can be concluded some problems of this thesis are:

1. How much power is needed to rotate a rotor based on the variation in the type of material used for the rotor?
2. How does the wind direction affect the performance of the flettner rotor as an alternative ship propulsion system?
3. How does the efficiency get affected by the variation of material and the wind direction?

1.3 Research Objectives

Based on problems mention above, the objectives of this thesis are:

1. To determine the power needed to rotate a rotor based on the variation in the type of material used for the rotor
2. To determine the performance of the flettner rotor as an alternative ship propulsion based on variation in wind direction

3. To determine the efficiency value based on variation in rotor's material and wind direction

1.4 Research Limitations

This thesis can be focused and organized, with limitations on problem which are:

1. Simulation is carried out by varying the rotor's material. Such as Aluminium, Zinc, Steel, and Stainless Steel
2. The simulation is carried out by varying the wind direction
3. Simulations are carried out using the Numeca Fine Marine (student licence) software and the others supporting software

1.5 Research Benefits

This thesis is expected to give benefits for the various kinds of parties. The benefits that can be obtained are:

1. Knowing the power needed to rotate a rotor based on the variation in type of material used for the rotor
2. Knowing the performance of the rotor based on wind direction variation
3. As a reference material for the next research discussion

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CHAPTER II
LITERATURE STUDY

2.1. Flettner Rotor

Figure 2. Flettner Rotor

Source *: forum.woodenboat.com*

In the early 1920s, Anton Flettner invented the Flettner rotor, an upright-mounted cylinder rotated by a motor (Flettner, 1925). He was a German aviation engineer and inventor that made important contributions to airplane, helicopter, vessel, and auto mobile designs (The New York Times, 1961). The flettner rotor itself is a cylindrical object located on the ship's body that rotates on its axis. This rotor helps the ship to utilize the airflow from the wind and generate additional thrust force by using the principle of magnus effect.

A flettner rotor typically consist of a cylinder with an endplate placed at the top of the cylinder. The rotor rotates by utilizing the action of a motor and starts to create a force also known as a lift force. The force is created by the rotation of the rotor that produce an accelerating air flow at the front of the cylinder and high-pressure air at the back of the cylinder, these phenomena known as the magnus effect create a force and push the object forward.

Basically, the rotor characteristic and its basic structure have to be defined in the technology options file before its usage for the model. As the model is generic with aim to be used with a several types of ships with different sized rotors, the rotor design produced will automatically base on the specific test ship if it is not pre-defined. There are several perimeters that affects the rotor coefficient performance for its implementation at ship.

2.1.1. Aspect Ratio

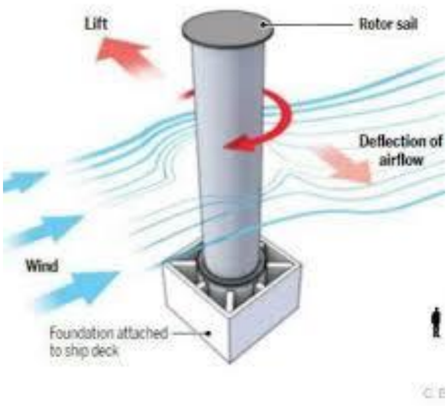

Figure 3. Aspec Ratio

Source: researchpublish.com

The main factor that contributes to Flettner Rotor effectiveness is the main shape of the rotor also known as the aspect ratio AR. The AR of Flettner device represents the ratio between height and diameter, changes its aerodynamic efficiency, as for higher AR value behaves much like a wing, with tip vortices that take part in the lift production. An important consideration is presented by Swanson (Swanson, 1961). An extensive comparison of the main data available in the literature on FR performances along with the other considerations, can be found in De Marco (De Marco, All.,2015). The equation for the aspect ratio can be write as follows:

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

Where,

AR = Aspect Ratio

H = Height of The Rotor (m)

D = Diameter of The Rotor (m)

2.1.2. Spin Ratio

Another factor that influence the aerodynamic characteristics of a FR are the spin ratio (i.e. the ratio between the circumferential speed of the rotor and the free stream velocity). The flow phenomenology around a circular cylinder is rather complex and consists of tip vortices and an alternate vortex shedding between the rotor sides. The flow phenomenology around a circular cylinder is rather complex and consists of tip vortices and an alternate vortex shedding between the rotor sides. It is known that vortex shedding occurs for Rn all the way up to at least Rn =8.0 E+06 (Seifert, 2012) . The equation for the spin ratio can be write as follows:

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

Where,

SR = Spin Ratio

Ω = Angular Velocity (rad/s)

U = Stream / Flux Velocity (m/s)

d = Diameter of The Rotor (m)

2.1.3. End Plate

The suggestion of applying an end plate on Flettner Rotor design was first suggested by Prandtl [4]. The purpose of using the plate is to optimize its aerodynamic efficiency. The modification at the top of the cylinder modifies the 3D flow phenomena at the tip of the Flettner Rotor increasing the “effective AR” of the rotor. A discussion of how the end plate size is related to SR in order to achieve optimal performances of the FR is presented by Seifert [Seifert, 2012). In his work Seifert observes that at low spin ratio (SR = 1.0) smaller plates generally give lightly smaller drag; for applications at moderate spin ratio (1.0 < SR < 3.0) larger plates are preferred, so as to delay the increase in induced drag, while, for high spin ratio applications (SR > 3.0), smaller plates are again more desirable.

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

Where,

EP = End Plate
de = Diameter End Plate (m)
d = Diameter (m)

2.2. Magnus Effect

Figure 4. Heinrich Gustav Magnus

Source: technology.matey.com

A long years ago, artillerist and ballistics experts along with the players of certain ball sports found unexpected spherical object's trajectories. Explained by B. Robins in early of 1742 for this event, he opined that these deviations in the spherical object's trajectories were due to the ball's rotation itself, Robins experimented with the sphere containing offset centre of gravity that resulted commensurate deflection in the actual path of the spheres (Prandtl, 1926). The Magnus effect itself, named after Heinrich Gustav Magnus, a German physicist who first investigate the phenomena and describe the effect in the year of 1852. Heinrich Gustav Magnus scientifically verified the eponymous effect by doing an experiment with a centrifugal blower that produce an air stream over a brass cylinder (Prandtl, 1926). However, in the year of 1672, Isaac Newton had described it and correctly concluded the cause after observing a tennis match back in his Cambridge college life (Glecik, 2004).

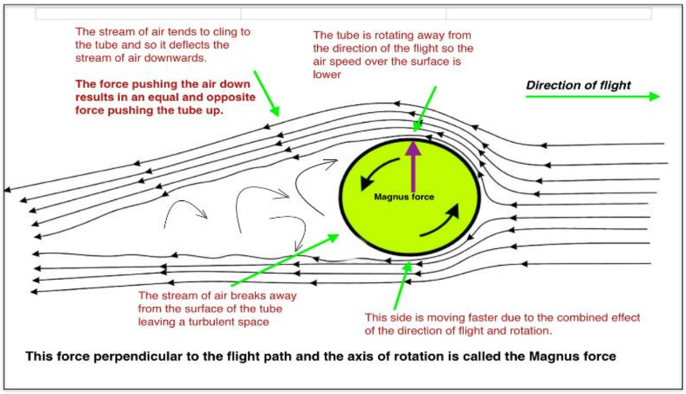

Figure 5. Magnus Effect

Source: medium.com

The Magnus effect commonly known with an object that rotates and moving through a fluid. It is a relatively simple exercise in aerodynamics. When an object is moving through the air, its surface is having a contact with a layer of air, this air known as the boundary layer. In the case of a sphere, the air in the boundary layer moves away from the surface, creating a low- pressure area behind the ball. The pressure differences in front to back region creates a backward force on the ball, which slows its forward movement. This is known as an aerodynamic drag or the normal air resistance, acts on any object moving through the air. However, if the sphere is rotating as it moves, the boundary layer is divided at several points on opposite sides of the ball. The upstream on the side of the ball is turning into an airflow, and the downstream on the side of the ball turning backward. As a consequence, the air flowing around the ball is turn aside, resulting in creating a low-pressure area behind the ball. This spinning motion of a sphere creates an effect which aims to generate a pressure difference across the ball, creating a lateral force component that pushes the ball sideways. This force working at the right angles to the forward motion of the ball is known as the Magnus force.

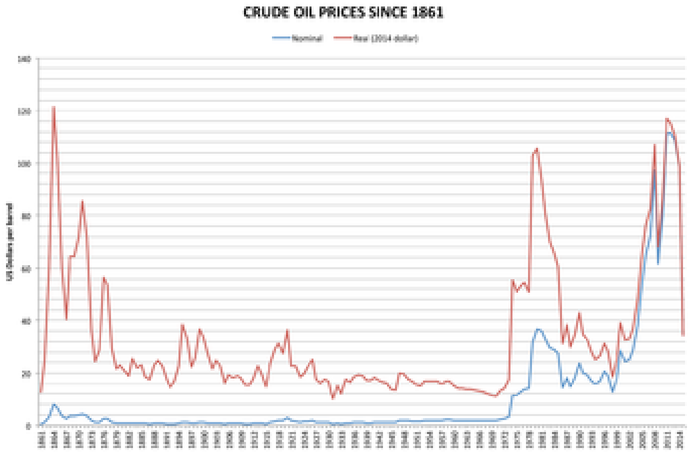

Figure 6. Crude Oil Price

Source: https://en.wikipedia.org/wiki/Price_of_oil

One of the example of Magnus effect utilization for the maritime sector is in the technology called “Flettner Rotors”. The rotor works as an alternative source of propulsion for the ship besides the conventional propulsion system that use fuel as a resource of energy. Although the technology is proven as an effective technological innovative solution in response to the post WWI energy crisis in the 1920s, it failed to enter the commercial shipping industry when real oil prices fell to their lowest ever level at the end of the decade (see Fig 2.2.3) (Nuttall. 2006). The technology was largely forgotten until the 1970/80s oil crisis situation where it was briefly re-examined to deal with the situation) (Nuttall. 2006). Flettner Rotor is relatively simple in its implementation and operation. It considered to have potential high application in various shipping scenarios ((Bergeson, 1981), 1981).

2.3. Computational Fluid Dynamic (CFD)

Computational Fluid Dynamic (CFD) is one of the analysis methods involving fluid flow, heat transfer and associated phenomena such as chemical reaction. It is a calculation method with a control of dimensions, area, and volume by utilizing computer computational help to perform calculations on each dividing element. Pressure distribution, flow velocity, mass flow rate, temperature distribution, and fluid flow pattern can be known at each point contained in the analysed system. The CFD simulation process consist of three main elements, which is pre-processor, processor/solver, and post processor.

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/Solver***

   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-Processing***

   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.

CFD method have several advantages that can be useful for the users such as helps the engineer to simulate a product so it does not take time and high cost, can lead to substantial reduction of time and cost of new designs, have the ability to study systems where controlled experiments are difficult, and practically unlimited of detail results.

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CHAPTER III
METHODOLOGY

3.1 Methodology Flow Chart

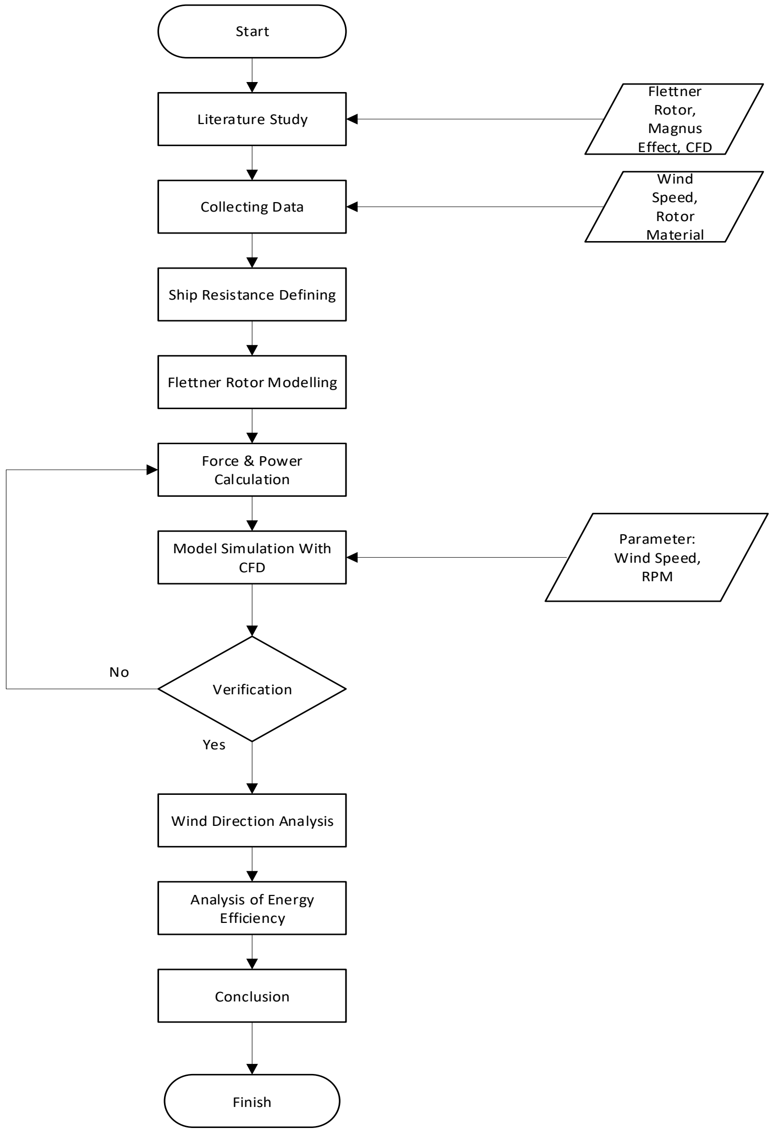

Figure 7. Methodology Flowchart

The Methodology Flow Chart shows the step of doing this final project research. The steps are shown in Figure 7

3.2 Definition of Methodology Flow Chart

1. **Literature Study**

   The first step is to conduct literature study for the research in order to understand better about the theories that might relate with the research project. Furthermore, literature study helps to enhance the validity of the project and helps to gather more information regarding any simulation that will be done. The resources for this research project including Guidelines, Books, Journals, and Articles with main discussion of this literature study includes:

   a. Flettner Rotor

   b. Magnus Effect

   c. CFD Theory

2. **Collecting Data**

   The next step is to collect data that related to Fluid Analysis of Flettner Rotor. The data needed for this research include:
   a. Flettner Rotor's Material
   b. Wind Speed
   c. Ship's Data

3. **Ship Defining**

   This step consists of defining the ship model that will be used for this project. Later, the model will be scaled up and calculated to determine its resistance for analysis with the rotor.

4. **3D Modelling**

   The three-dimension modelling of the flettner rotor is made using Inventor software. The results of the 3D model are expected to be simulated by the FINE Marine software to get the desired data.

5. **Force Calculation**

   Force calculation is carried out to calculate the force based on the rotor design. It is calculated by using numerical formula which going to be a reference for the simulation result

6. **Power Calculation**

   Power calculation is carried out to calculate the amount of power needed to rotate the rotor based on variation in flettner rotor's material.

7. Model Simulation with CFD

Simulations on flettner rotor model are made on several possible software modellers that can be supported by simulation software with various variations on wind speed and rotor rotational speed. The rotor model that has several variations at this stage will be simulated using the Numeca Fine ™ Marine which will produce several different running results.

8. Analysis of Wind Direction

After the power and force value is obtained, the process of varying wind direction is starting with goals to understand the effect of force produce to the ship movement.

9. Analysis of Energy Efficiency

At this stage, there will be calculations conducted on running results based on simulation process on the software. It combines previous calculation and analysis to determine the energy efficiency during rotor rotational event based on the fuel consumption of the ship and the rotor itself.

10. Conclusion

The final step in this final project is to conclude from the results of the force, power, efficiency and data analysis conducted after simulating several models with variations in the rotor materials and the wind direction. The results of the analysis taken are the results with the biggest force generated and the biggest fuel saved. This stage will also draw conclusions from a series of final assignments and submit suggestions that can be used as references for further research and development.

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CHAPTER IV
DISCUSION AND RESULT

4.1. Ship's Resistance Defining

The first step of this project is to define the ship's that will be used. This project 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.

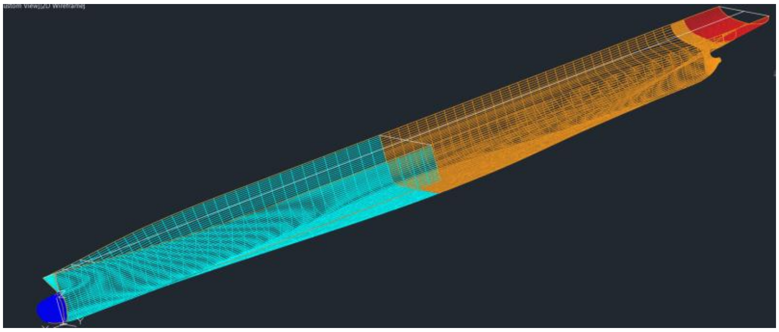


Figure 8. Ship Model

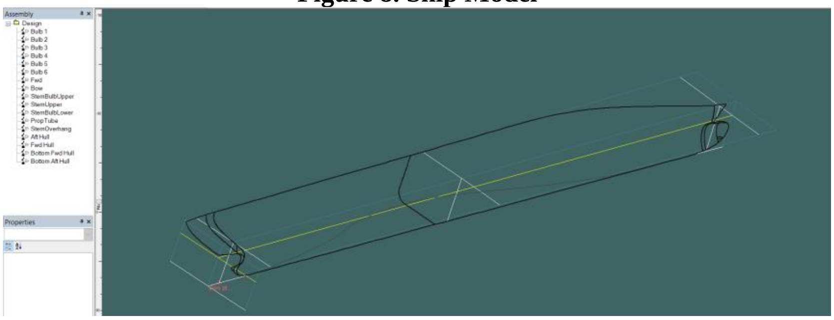


Figure 9. KRISO-KCS Ship Model

4.1.1 Scaling the Model

Now begin with scaling up the model, when ship's model has been selected, go to the surface menu and select size surfaces. There's an option showing the current dimension of ship model, going together with these dimensions there's a check box called proportional scaling, re-scale markers and re scale curves. Choose "Select All" and Check these proportional scaling boxes and type the desired dimension. For this project, the ship's length will be up to 119 meters long. Type these number in the "length" box and select ok. It will automatically scale up the ship's model

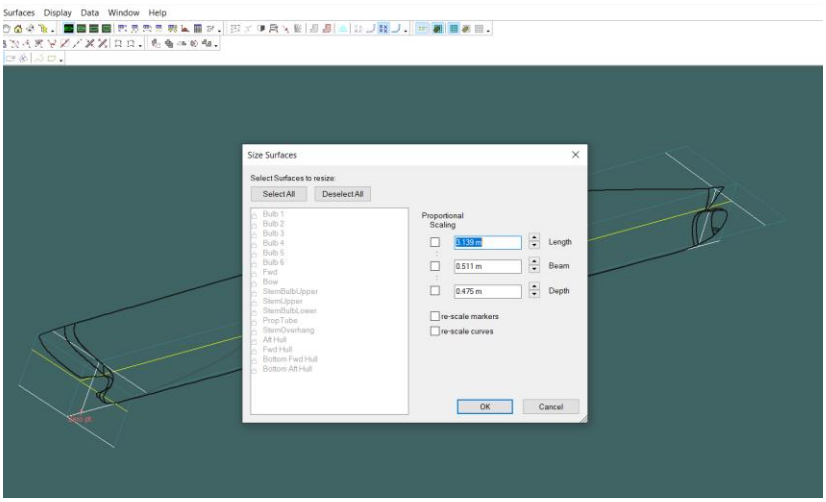


Figure 10. Size Surface Option

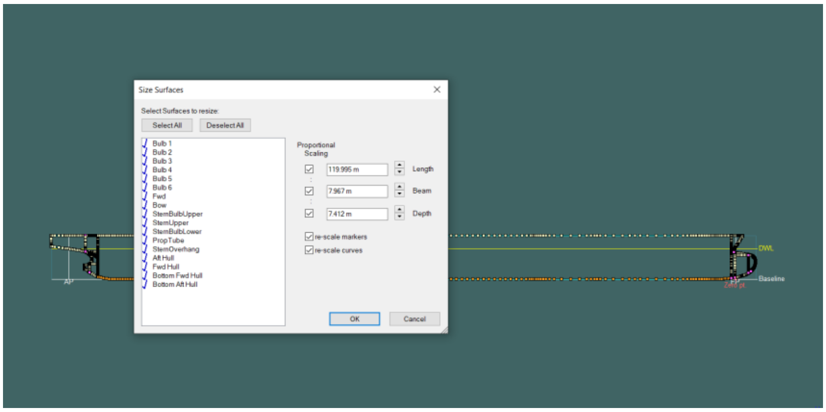
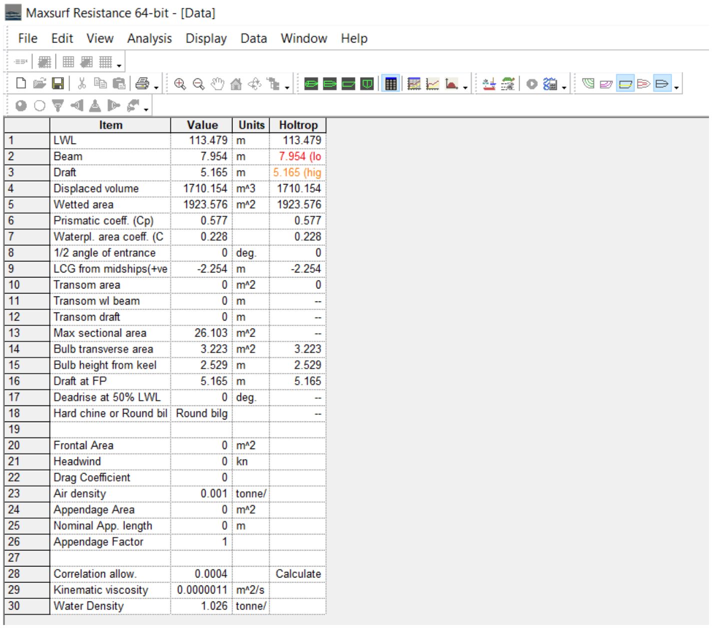


Figure 11. Scalling Option

4.1.2 Resistance Calculation

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 project, 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.



	Item	Value	Units	Holtrop
1	LWL	113.479	m	113.479
2	Beam	7.954	m	7.954 (lo
3	Draft	5.165	m	5.165 (hig
4	Displaced volume	1710.154	m^3	1710.154
5	Wetted area	1923.576	m^2	1923.576
6	Prismatic coeff. (Cp)	0.577		0.577
7	Waterpl. area coeff. (C	0.228		0.228
8	1/2 angle of entrance	0	deg.	0
9	LCG from midships(+ve	-2.254	m	-2.254
10	Transom area	0	m^2	0
11	Transom wl beam	0	m	--
12	Transom draft	0	m	--
13	Max sectional area	26.103	m^2	--
14	Bulb transverse area	3.223	m^2	3.223
15	Bulb height from keel	2.529	m	2.529
16	Draft at FP	5.165	m	5.165
17	Deadrise at 50% LWL	0	deg.	--
18	Hard chine or Round bil	Round bilg		--
19				
20	Frontal Area	0	m^2	
21	Headwind	0	kn	
22	Drag Coefficient	0		
23	Air density	0.001	tonne/	
24	Appendage Area	0	m^2	
25	Nominal App. length	0	m	
26	Appendage Factor	1		
27				
28	Correlation allow.	0.0004		Calculate
29	Kinematic viscosity	0.0000011	m^2/s	
30	Water Density	1.026	tonne/	

Figure 12. Ship Data

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.

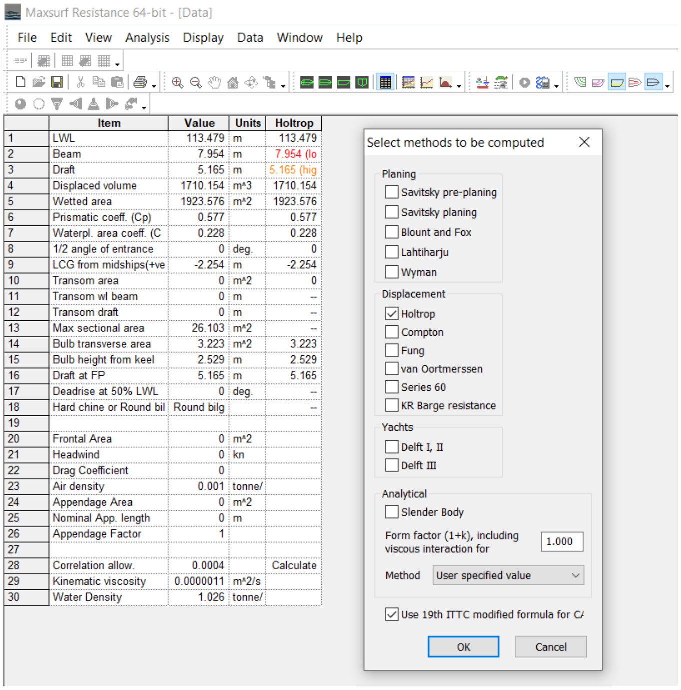


Figure 13. Methods Selection

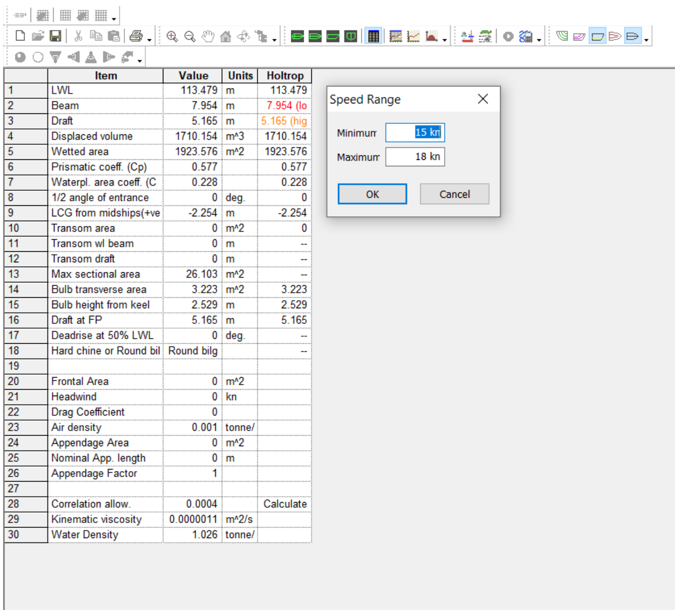


Figure 14. Speed Variation

	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
33	15.200	0.234	0.722	146.9	1148.742
34	15.300	0.236	0.727	149.1	1173.186
35	15.400	0.237	0.732	151.2	1197.994
36	15.500	0.239	0.736	153.4	1223.167
37	15.600	0.241	0.741	155.6	1248.706
38	15.700	0.242	0.746	157.8	1274.612
39	15.800	0.244	0.751	160.0	1300.883
40	15.900	0.245	0.755	162.3	1327.523
41	16.000	0.247	0.760	164.6	1354.530

Figure 15. Analysis Result

Based on the result above, it is stated that the resistance value of the ship on 15 knots is 142.7 kN

4.2. Flettner Rotor Creation Process

On post processing simulation, can be obtained calculation results of simulation for fluid temperature.

4.2.1 Approximate Flettner Dimension Design

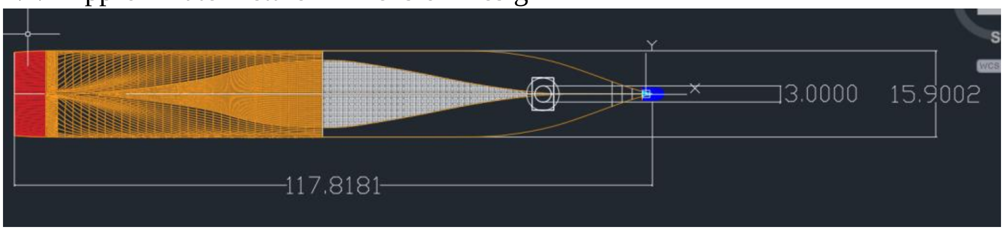


Figure 16. Ship Dimension For Flettner Rotor Installation

Ship's resistance and its dimension are already defined. Now from the ship's model, Flettner Rotor dimension is able to be selected. Based on

4.2.2 Flettner Rotor Design

Now the process of designing Flettner Rotor can begin. In this project, rotor's parameter such as its dimension, RPM, and the other is referring to the graph **Figure 17 and Figure 18** 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.

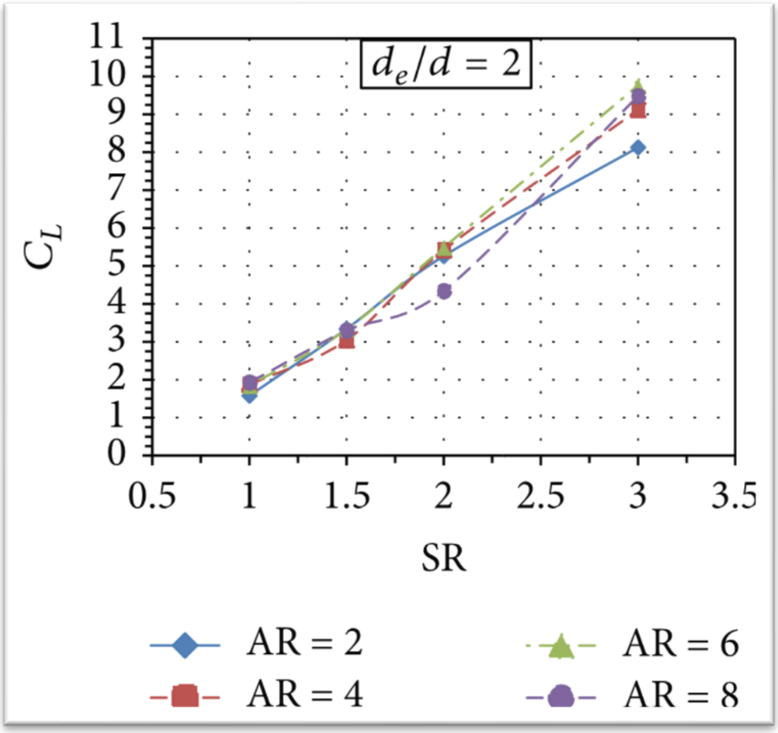


Figure 17. AR SR CL Graph

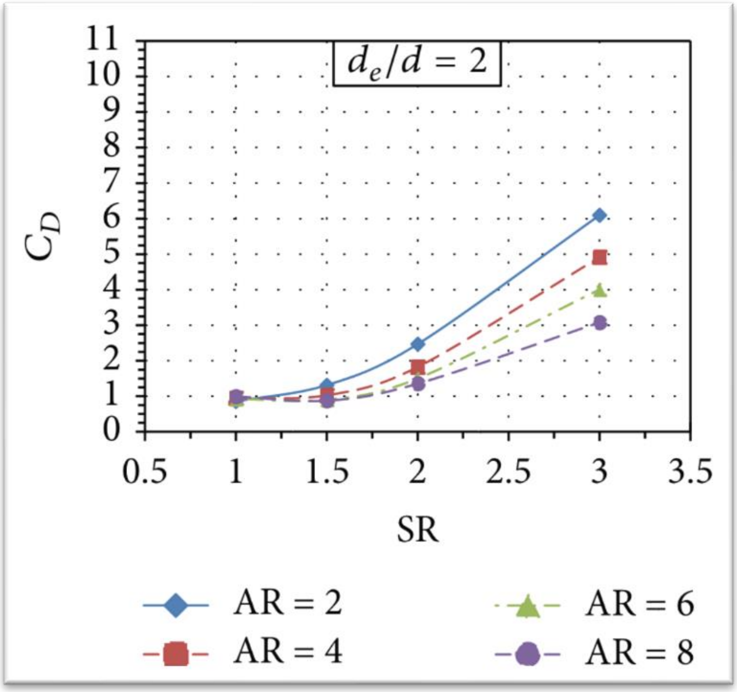


Figure 18 AR SR CD Graph

The first parameter to determine is the Aspect Ratio (AR). 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 project 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.

- Aspect Ratio

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

Where,

AR = Aspect Ratio

H = Height (m)

d = Diameter (m)

Known:

AR = 6 (Choosing from the graph)
d = 3 (m)

$$6 = \frac{H\ (m)}{3\ \ (m)}$$

H = 18 (m)

Next parameter to be determine is the Spin Ratio (SR). 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 project 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. Below is the example of calculation.

- Spin Ratio

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

Where,

SR = Spin Ratio
Ω = Angular Velocity (rad/s)
d = Diameter (m)
u = Flux Velocity (m/s)

Known,

SR = 3 (Choosing from the graph)
d = 3 (m)
u = 7.2 (m/s)

$$3 = \frac{\Omega \ \left(\frac{rad}{s}\right) \times 3(m)}{2 \times 7.2\ (m)} \qquad (2)$$

Ω = 14.4 (rad/s)

Table 1 SR Value with variation in flux Velocity and RPM.

Flux Velocity (m/s)	SR	diameter (m)	Angular Velocity (rad/s)
7.2	3	3	14.4
6.9	3	3	13.8
6.3	3	3	12.6
5.6	3	3	11.2
4.5	3	3	9
2.7	3	3	5.4

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. Based on the graph, the end plate value chosen for this project is 2 resulting in the value of Diameter End Plate to become 6 meter.

- End Plate

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

Where,

EP = End Plate
de = Diameter End Plate (m)
d = Diameter (m)

Known,
EP = 2 (Choosing from the graph)
d = 3 (m)

$$2 = \frac{de\ (m)}{3\ (m)} \quad (3)$$

de = 6 (m)

The last step of designing flettner rotor to determine the rotor's material. On this project the rotor's material will be varied to determine it's power consumption.

- Material

On material variation, it is assumed that material strength for all materials is the same. It will only focusing on the mass produce based on the design and the power needed to rotate the rotor.

Table 2 List of Materials.

No	Material	Density (kg/m^3)
1	Steel	7850
2	Aluminum	2700
3	Stainless Steel	8000
4	Zinc	7000

- Summary

1. Ship's Data

LOA	= 117.8 (m)
B	= 15.9 (m)
D	= 5.165 (m)
Resistance	= 142.7 kN
Power	= 1100,948 kW

2. Flettner Rotor Dimension

AR	= 6
SR	= 3
Height	= 18 (m)
Diameter	= 3 (m)
Diameter Out.	= 6 (m)

3. Variables and Materials

Table 3 Summary Table

No	Material	Density (kg/m3)	Flux Velocity (m/s)	Angular Velocity (rad/s)
1	Steel	7850	7.2	14.4
2	Steel	7850	6.9	13.8
3	Steel	7850	6.3	12.6
4	Steel	7850	5.6	11.2
5	Steel	7850	4.5	9
6	Steel	7850	2.7	5.4

7	Alumunium	2700	7.2	14.4
8	Alumunium	2700	6.9	13.8
9	Alumunium	2700	6.3	12.6
10	Alumunium	2700	5.6	11.2
11	Alumunium	2700	4.5	9
12	Alumunium	2700	2.7	5.4
13	Stainless Steel	8000	7.2	14.4
14	Stainless Steel	8000	6.9	13.8
15	Stainless Steel	8000	6.3	12.6
16	Stainless Steel	8000	5.6	11.2
17	Stainless Steel	8000	4.5	9
18	Stainless Steel	8000	2.7	5.4
19	Zinc	7000	7.2	14.4
20	Zinc	7000	6.9	13.8
21	Zinc	7000	6.3	12.6
22	Zinc	7000	5.6	11.2
23	Zinc	7000	4.5	9
24	Zinc	7000	2.7	5.4

When the process of selecting Flettner Rotor design is completed, the process is proceeding to the next step which is the force calculation.

4.2.3 Force Calculation

Now, when the value of Aspect Ratio, Spin Ratio, End Plate, and Rotor's Material has been selected, these values can help to identify the amount of force generated. The first force value to be calculated is the lift force and the second one is a drag force. Both calculations are done by referring to the graph created by A. De Marco (De Marco, 2016) which provide the Coefficient Lift (CL) and Coefficient Drag (CD) value based on the selected value of aspect ratio (AR) and spin ratio (SR).

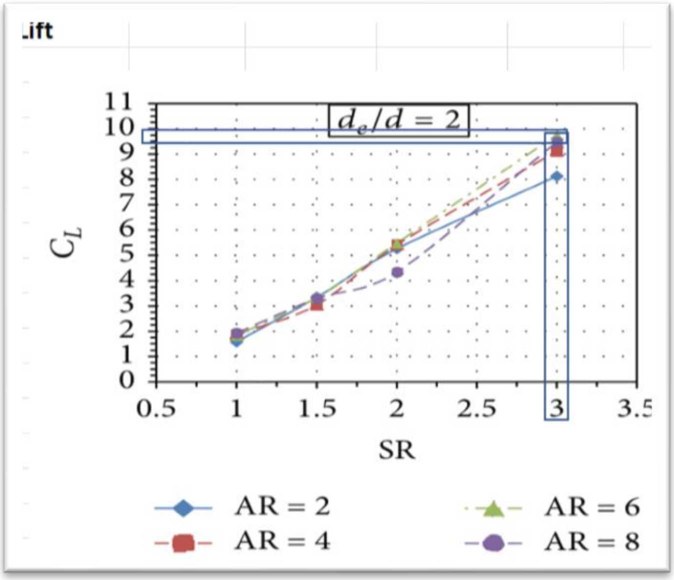


Figure 19. CL Graph

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. It is calculated by using the formula:

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

Where,

CL = Coefficient Lift

L = Lift (N)

ρ = Density (kg/m^{3})

A = Area (m^{2})

u = Flux Velocity (m/s)

For Example,

CL = 9.5

ρ = 1.2 (kg/m^{3})

A = 54 (m^{2})

u = 7.2 (m/s)

$$9.5 = \frac{L\ (N)}{0.5 \times 1.2\ (kg/m^3) \times\ 54\ (m^2) \times\ 7.2^2\ (m/s)} \quad (4)$$

L = 31912.7 (N)

Table 4 Lift Force Generated

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

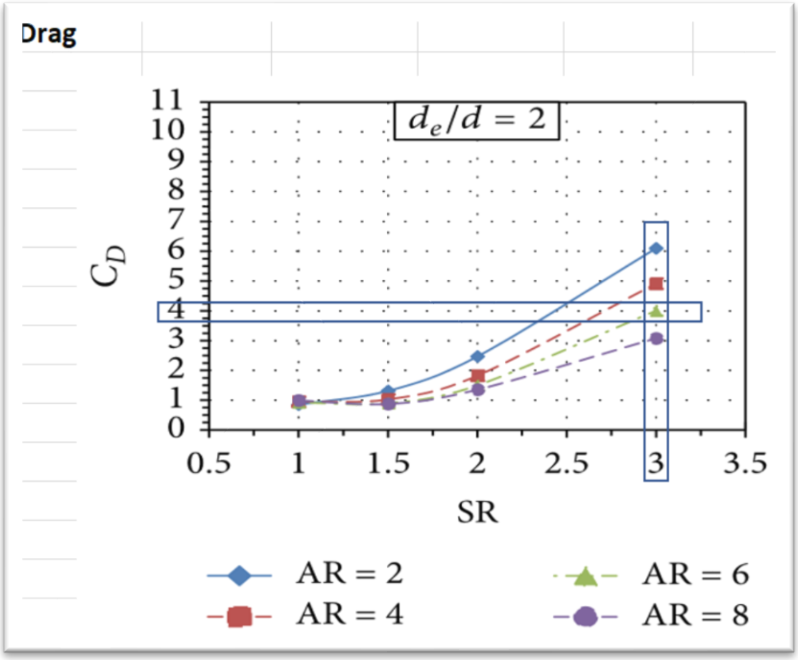


Figure 20. CD Graph

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. It is calculated by using the formula:

$$CD = \frac{D\ (N)}{0.5 \times \rho\ (kg/m^3) \times A\ (m^2) \times U^2\ (m/s)} \qquad (5)$$

Where,

CD = Coefficient Drag

D = Drag (N)

ρ = Density (kg/m^3)

A = Area (m^2)

u = Wind Velocity (m/s)

For Example,

CD = 4

ρ = 1.2 (kg/m^3)

A = 54 (m^2)

u = 7 (m/s)

$$4 = \frac{D\ (N)}{0.5 \times 1.2\ (kg/m^3) \times\ 54\ (m^2) \times\ 7^2\ (m/s)} \qquad (5)$$

D = 1814.4 (N)

Table 4 Drag Force Generated based on Flux velocity and Rotation variation

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

So, based on selected SR and AR values, on 7.2 m/s wind speed this flettner rotor can generate 30164 N lift force, 1814.4 N drag and on 2.7 m/s wind speed, the flettner rotor can generate 4487.24 N lift force, 699.84 drag force. Now moving on to the next step there is power calculation

4.2.4 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. The first step is to calculate the angular acceleration. Angular acceleration defined as the rate of change per unit time of angular velocity and comes with the symbol of α. It is calculated by using the formula of:

$$\boldsymbol{\alpha}\ (rad/s^2) = \frac{\Omega\ \left(\frac{rad}{s}\right)}{t(s)} \qquad (6)$$

Where,

Ω = Angular Velocity (rad/s)

t = Time Taken (second)

α = Angular Acceleration (rad/s2)

For Example:

Ω = 14.4 (rad/s)

t = 10 (second)

$$\boldsymbol{\alpha}\ (rad/s^2) = \frac{14.4\ \left(\frac{rad}{s}\right)}{10(s)} \qquad (6)$$

α = 1.44 (rad/s2)

When the α is determined, the second step is to calculate the Inertia Moment of the rotor. Inertia moment is a rotating body's resistance to its angular acceleration or deceleration. It comes with the symbol of I and calculated by using the formula:

$$I = m\,(Kg) \times r^2 (m) \qquad (7)$$

Where,

m = Mass (Kg)

r = Radius (m)

I = Inertia Moment (Kg/m^2)

For Example,

m = 1220.840 (Kg)

r = 1.5 (m)

$$I = 1220.84\,(Kg) \times 1.5^2 (m) \qquad (7)$$

I = 2746.89 (Kgm^2)

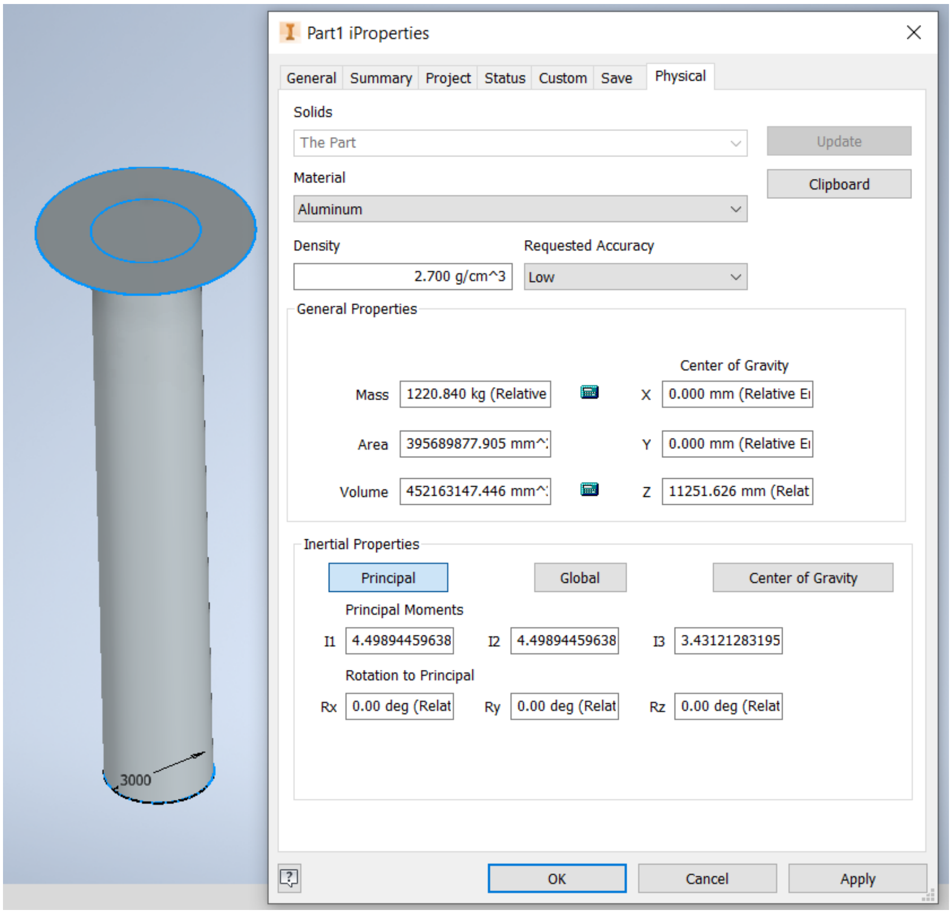


Figure 21. Object Properties

The mass value for the calculation comes from Flettner Rotor design based on material being used. Then when these values of Angular acceleration and Inertia moment has been determined, then the torque value is able to be calculated. 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. It is calculated by using the formula:

$$T\ (Nm) = I\ (kgm2) \times \alpha\ (rad/s^2) \qquad (8)$$

Where,

I = Inertia Moment (Kgm^2)

α = Angular Acceleration (rad/s^2)

T = Torque (Nm)

For Example,

I = 2746.89 (Kgm^2)

α = 1.44 (rad/s^2)

$$T\ (Nm) = 2746.89\ (kgm2) \times 1.4\ 4(rad/s^2) \quad (8)$$

T = 3955.52 (Nm)

And the last step is to get the value of Power. Power is the rate of doing work per unit of time. The output power of an electric motor is the product of the torque produced by the motor and its output shaft angular velocity. It is calculated by using the formula:

$$P\ (kW) = \frac{T\ (Nm) \times\ \Omega\ (RPM)}{5252} \times\ 0.745 \quad (9)$$

Where,

T = Torque (Nm)

Ω = Angular Velocity (rad/s)

P = Power (kW)

For Example,

T = 3955.52 (Nm)

Ω = 14.4 (rad/s)

= 137.5 (RPM)

$$P\ (kW) = \frac{3955.52\ (Nm) \times\ 137.5\ (RPM)}{5252} \times\ 0.745 \qquad (9)$$

P = 77.22 KW

Table 5 Power Calculation Result

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

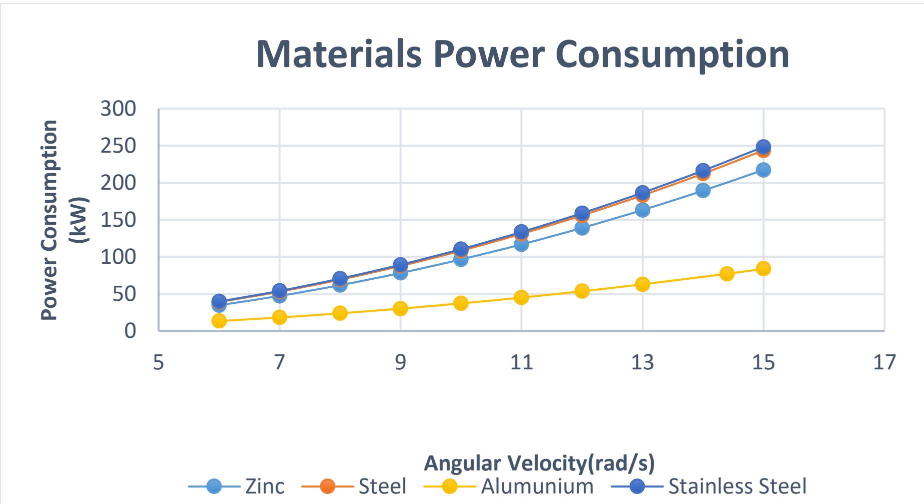


Figure 22. Power Graph Consumption

Based on calculations above, stainless steel materials have the biggest power range for each speed to rotate the flettner rotor with the range of 32.178 kW - 228.82 kW. And for the smallest power consumption is aluminium with the range of 10.86 kW – 77.22 kW.

4.3. Simulation Process

4.3.1 Modelling Process

The simulation process is consisted of several steps that needs to be done. The first step is modelling procees. In general, there are 2 main field required in this process which is the cylinder rotor field and the box field. The cylinder field is where will the force be determined and the box field is where fluid flows during simulation.

First, the cylinder rotor field modelling process take places. Using Autodesk Inventor 2020, the flettner rotor model design process referring to geometry aspect that has been set and calculated. During the process of modelling, there are factors needs to be considered. First of all, it is required to take a look at the ship's dimension. Since it will need space, finding spaces available on the ship and think where is the right place to install is an obligation to install the rotor onboard. After the information for spaces is finished, now proceed to geometry determination. The design itself consist of cylinder and an endplate at the top of the cylinder. Value of height, diameter, and endplate are based on the graph made on previous research. It contains information that helps the author determine the rotor's geometry. Next, proceed to draw the flettner rotor based on the selected value and material.

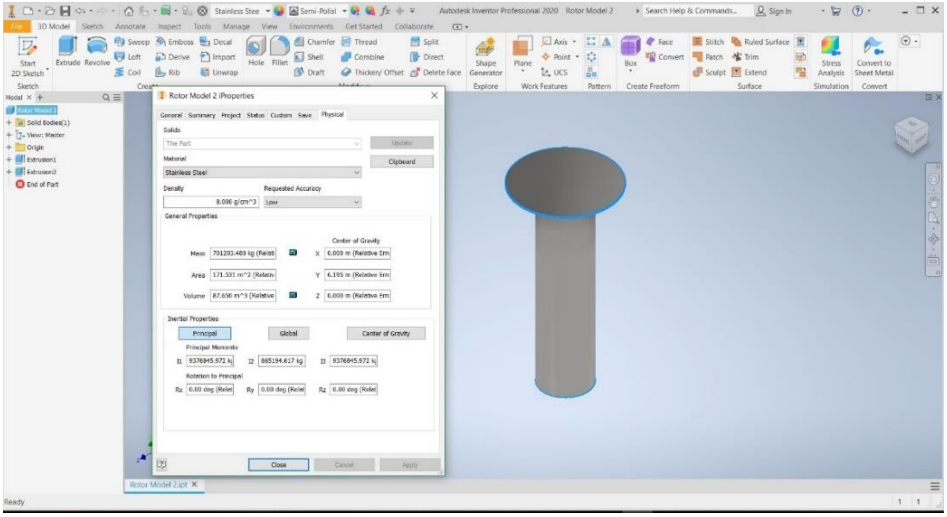


Figure 23. Properties of Flettner Rotor Model

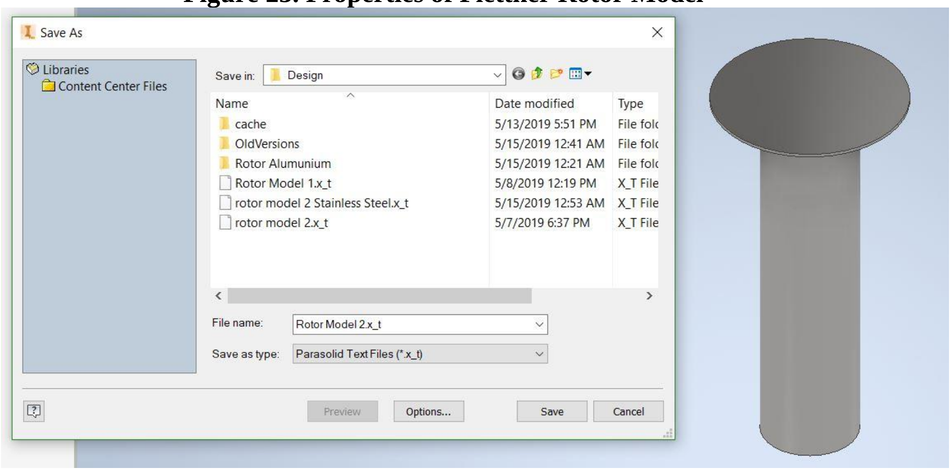


Figure 24. Saving File

When it’s done, it gives directly calculated value of mass, volume, and area. Those value are shown in iProperties and it comes with another value as well such as center gravity, density, etc. After finished, save the file, export it into Parasolid form and proceed into the second step which is the box field modelling process.

For the second step, Fine software will be used. This software will also be used to run the simulation. Now, for the modelling of the box, select “Import Parasolid model to start and choose the flettner rotor model in Parasolid form file. There will be a cylinder solid form come up and that is the previous cylinder model design. Next, on top of the left side corner it provides various option. Select create box and there will be blank coordinates needs to be filled to create a box.

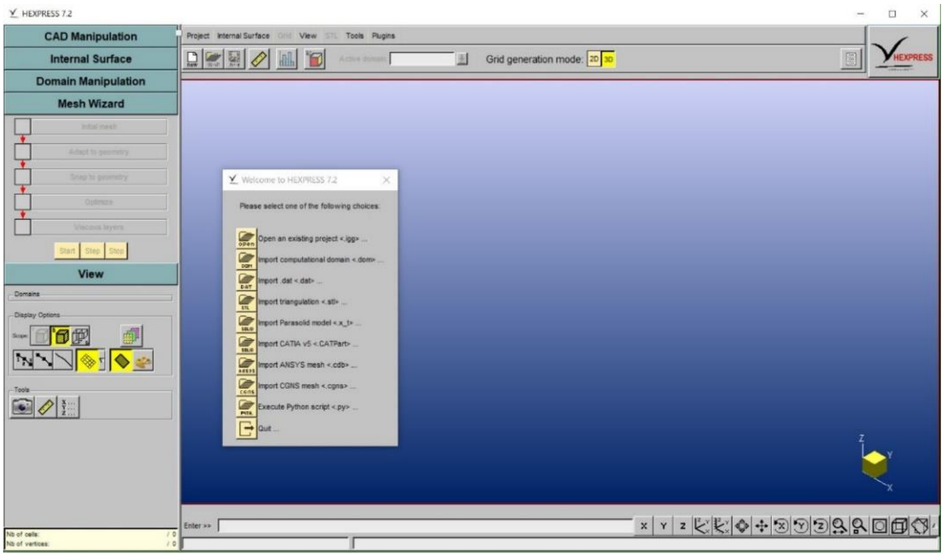


Figure 25. Fine Hexpress

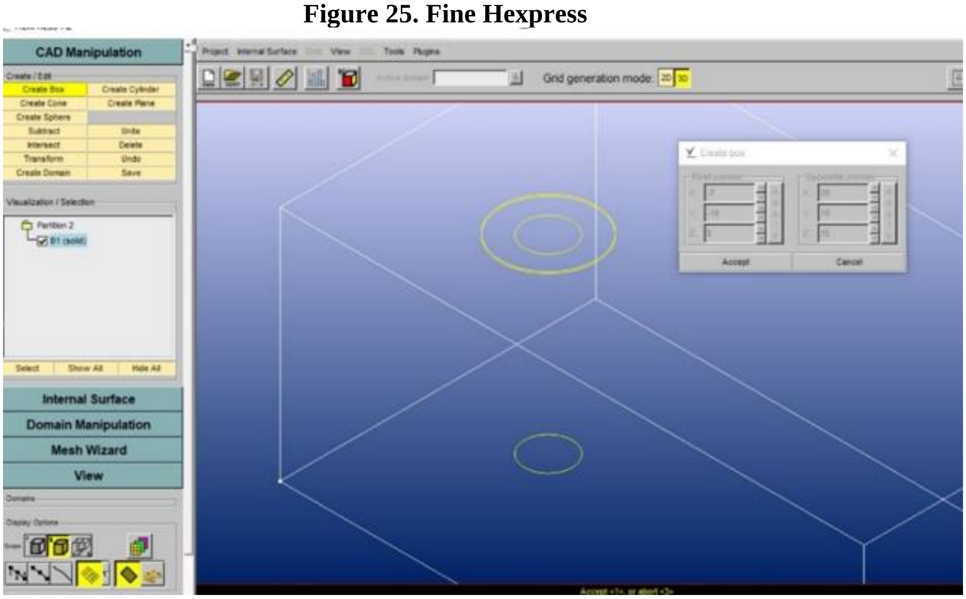


Figure 26. Creating Box Field Togetheer with Cylinder Field

When it finished, these 2 objects are going through the process of substract. This process used to identify which field that will be flowed. Pick command “substract”, select the box section and press ok. Then directly select the object section and press perform. Now, a domain can be created.

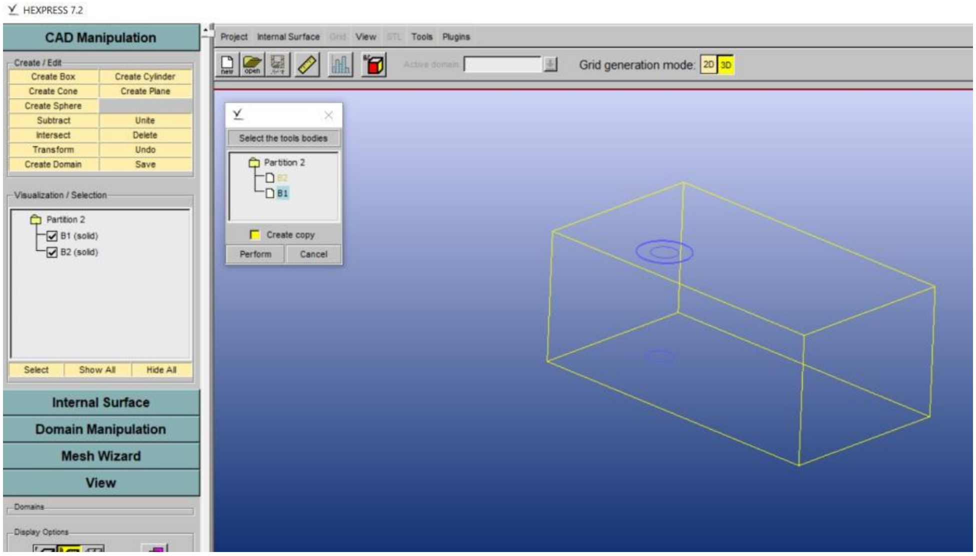


Figure 27. Substract Process

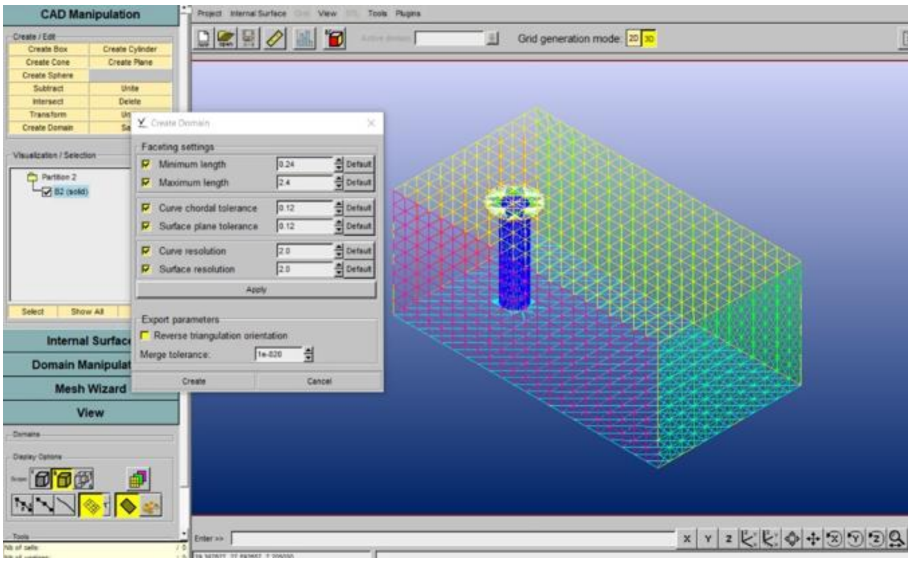


Figure 28. Domain Creation

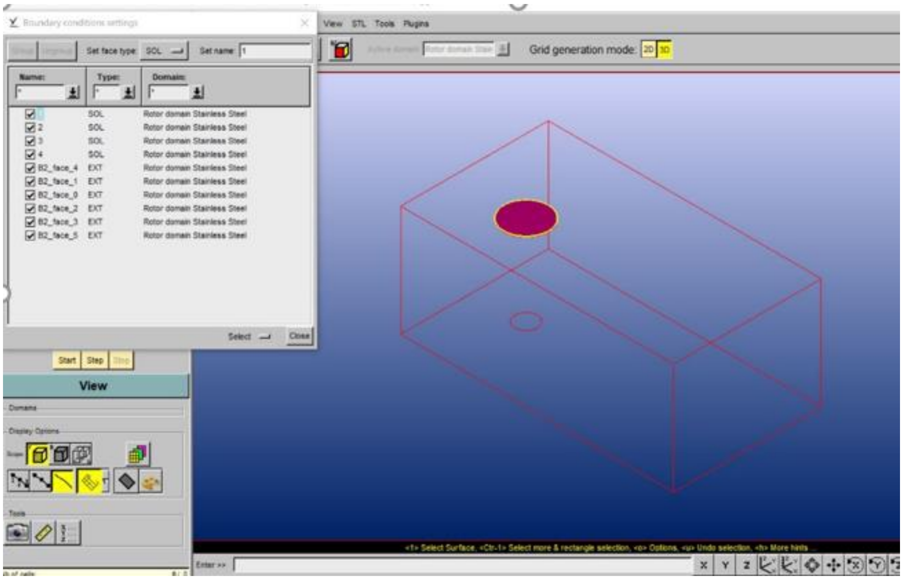


Figure 29. Boundary Settings

Select the object, pick “Create Domain”and then choose “Create”. When a domain has been created, set the boundary condition for the domain. Boundary condition is to assign position of inlet and outlet for the fluid. For the wind, it is arranged that the wind will come from + Y axis towards –Y axis which located opposite on right and left of the rotor. “SOL” which represent solid is used for the rotor and “EXT” which represent external is used for the face around the rotor.

Next step is meshing process. Meshing is defined as the process of dividing the whole component into a number of elements so that whenever the load is applied on the component it distributes the load uniformly. Meshing is an important part of the computeraided engineering simulation process since it influences the accuracy, convergence and speed of the solution. The more detail the solid mesh, the more it takes time to run the simulation process.

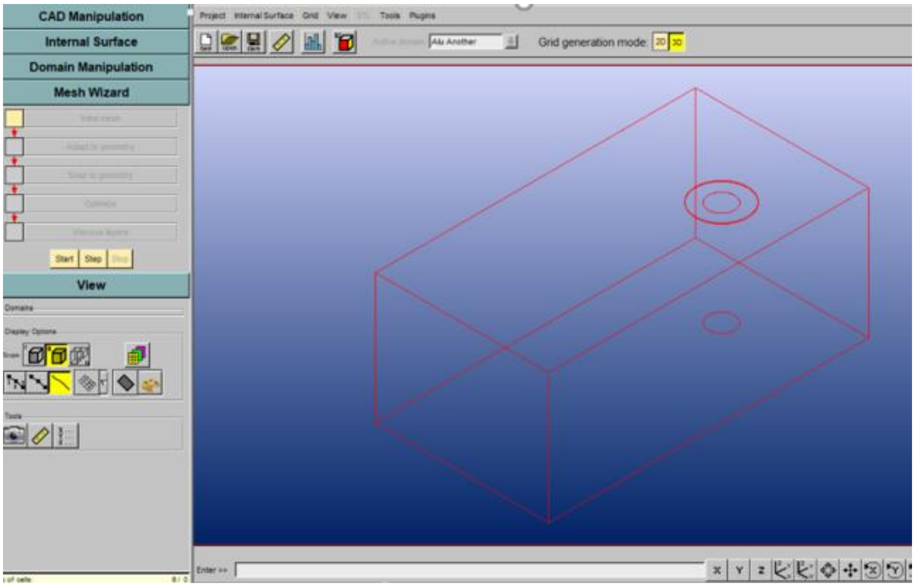


Figure 30. Initial Meshing Settings

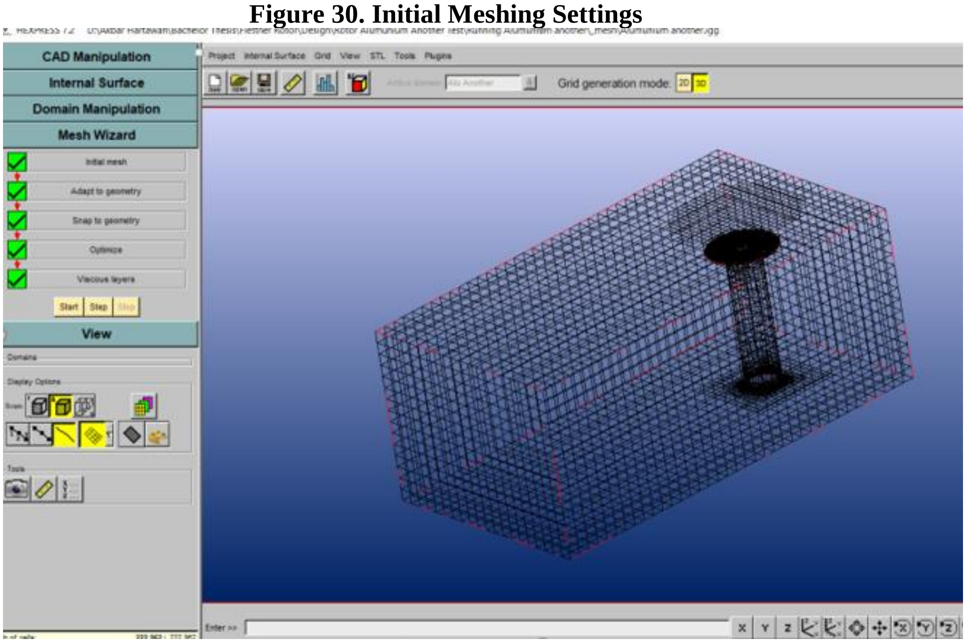


Figure 31. Meshing Process Completed

4.3.2 Parameter Input Process

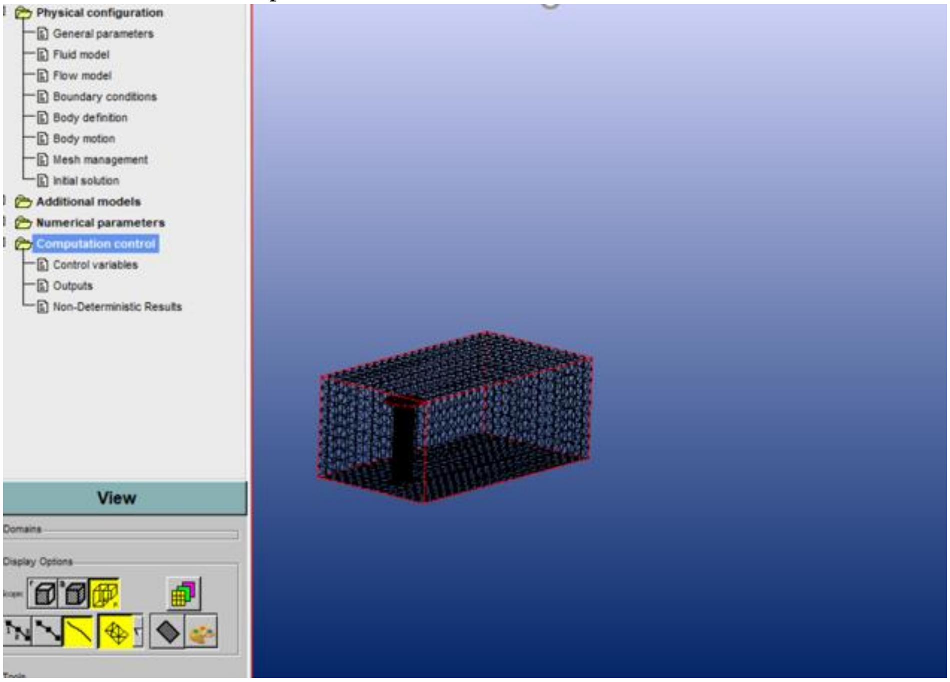


Figure 32. Parameter Input For Simulation

When the process of modelling is complete, now the process of inputting parameters can be started. There are various parameters needs to be fullfiled before running the simulation such as general parameters, fluid model, flow model boundary conditions, body definition and motion, mesh management, initial solution and the computational control. These parameters is to be set depends on project desired condition. On this project, the parameters is to be set on:

- General Parameters : Unsteady
- Fluid Model
  - Name : Air
  - Dynamic Viscosity : 1.85e-005 [Pa.s]
  - Density : 1.2 [kg/m2]
- Flow Model

- Regime/Turbulence : k-omega (SST-Menter)
- Reference Length : 3 [m]
- Reference Velocity : (7.2-2.6) [m/s]

- Boundary Conditions
  - Vy Velocity : Variation

- Body Definition
  - Definition : Assign to Rotor

- Body Motion
  - RZ0 Motion type : Imposed
  - Motion law : Constant (Varied)

- Mesh Management : Activate to rotating Framing Method

- Initial Solution
  - Vy Velocity : Variation

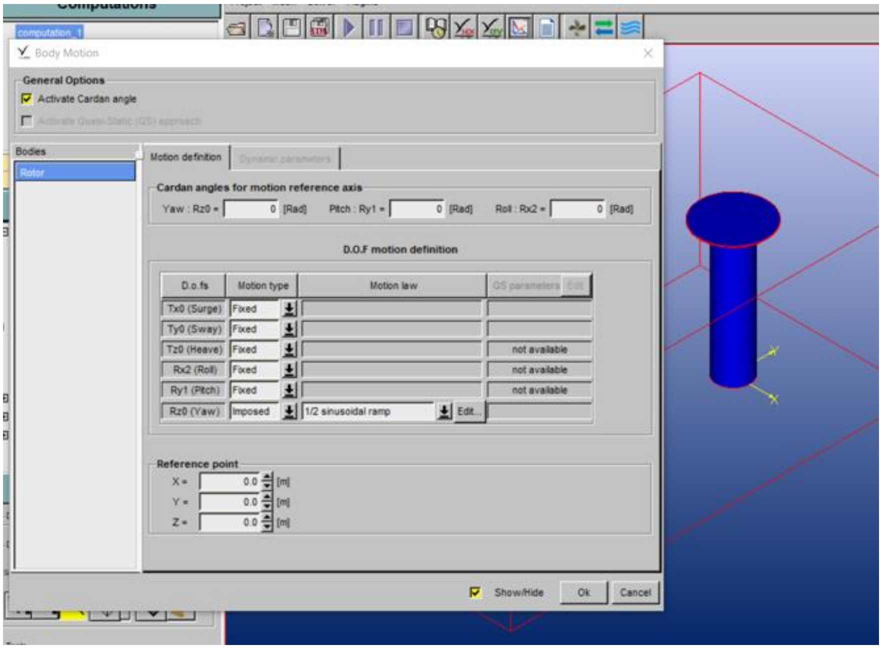


Figure 33. Body Motion Settings

4.3.3 Running Solver Process

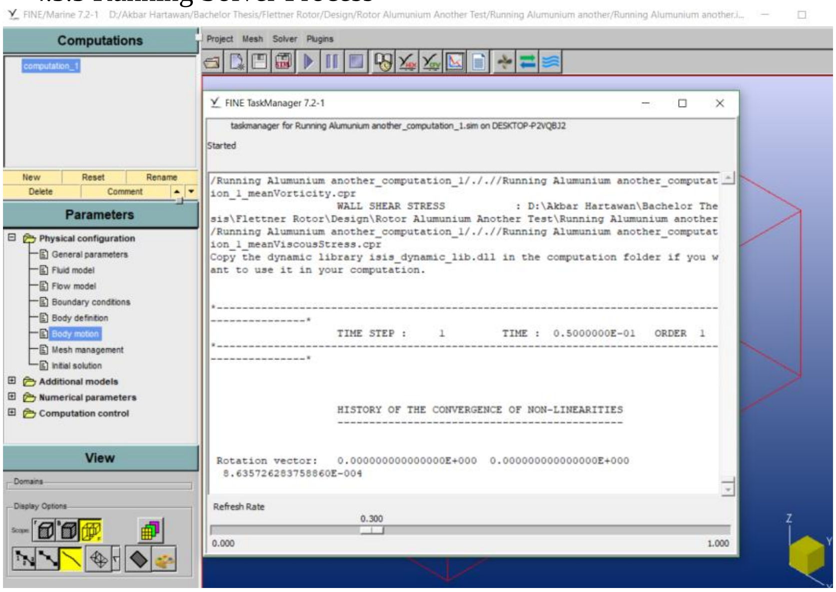


Figure 34. Fine Task Manager

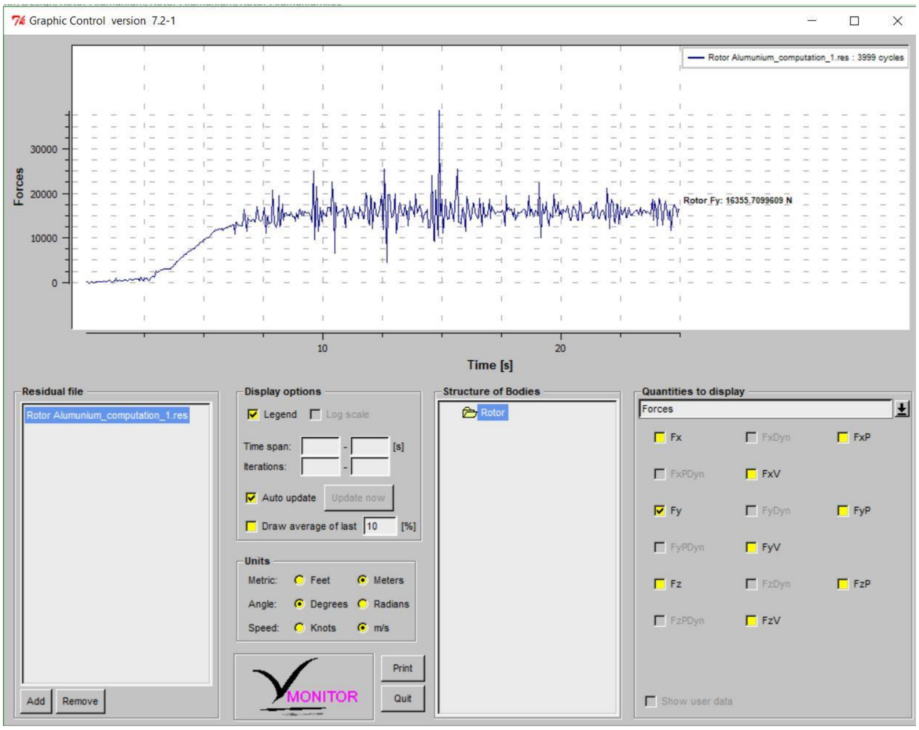


Figure 35. Monitor Graphic Control

Running solver process is the stage of calculation for every iterations in parts associated with the mesh configuration and the parameters/ method being inputed. This process takes quite a long time based on object and parameters being inputed. While the solver is running, during the process it also provides data resulted by the solver. These data can be monited by choosing “start monitor” command. And when the process is finished, it comes up with notification as you can see in figure below.

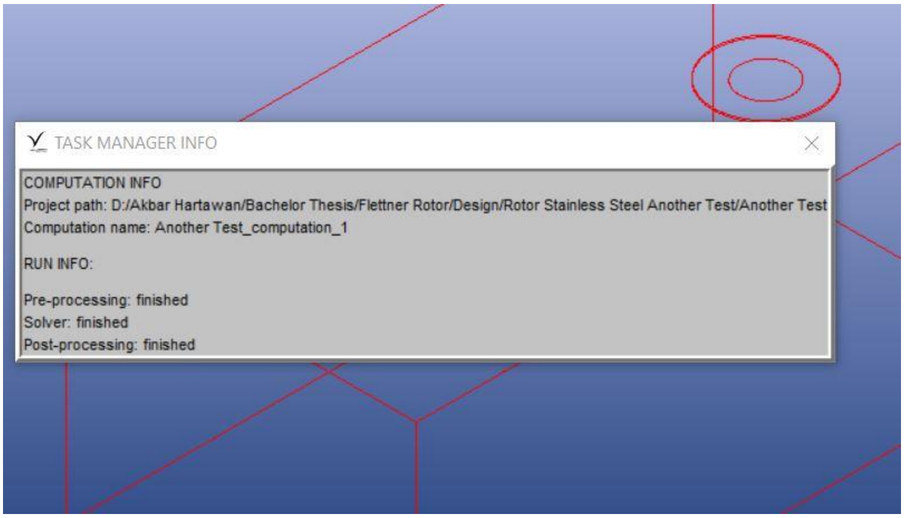


Figure 36. Task Manager Info

4.3.4 Simulation Result

Now when the task manager info command is up and the run info is all finished, the result will be able to be seen. Choose "Start result analysis" command for the force resulted by the analysis and choose "CF View" command to see the flow produce during the simulation.

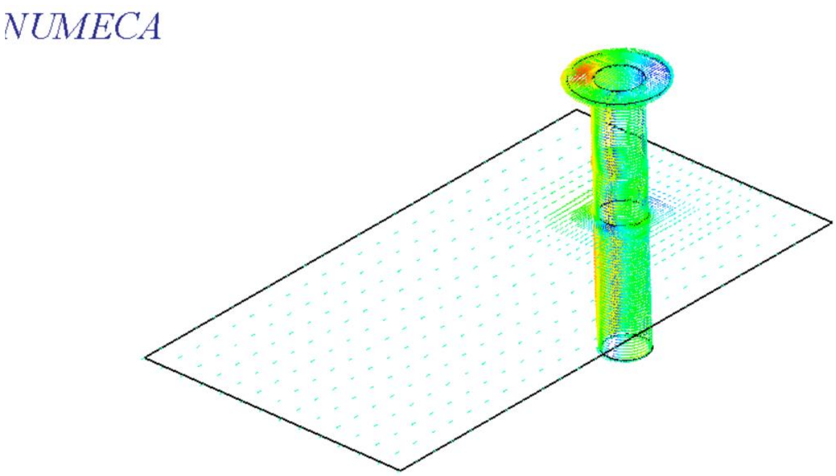


Figure 37. Flettner Rotor Running Result on CFView

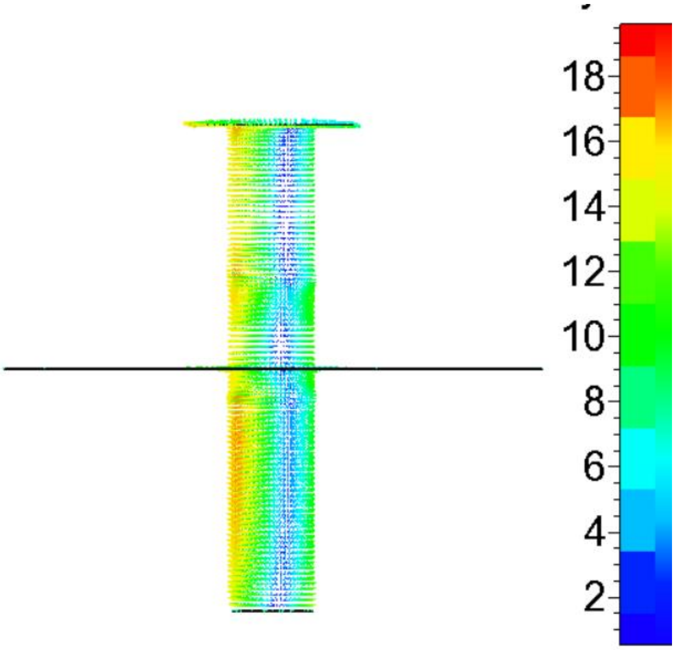


Figure 38. Simulation Result

Table of quantity values (filtered quantities are marked by *)
Common quantities

T	Fy(FR)	Fx(FR)	Fz(FR)	Resultan	Cos	Degree		Average Fy	=	26901.36
0.5	28476.69	5467.069	436.9025	28996.74	0.999853	0.982065		Average Fx	=	-1219.68
1	30081.94	178.2727	361.8883	30082.47	0.999848	0.999982		Average Resultai	=	26931.88
1.5	29664.24	-1186.57	376.4928	29687.96	0.999848	0.999201		Degree	=	0.998869
2	29287.45	-1092.05	374.9351	29307.8	0.999848	0.999306				
2.5	29139.15	-1034.12	375.7334	29157.49	0.999848	0.999371				
3	29032.52	-1012.1	380.2314	29050.16	0.999848	0.999393				
3.5	28926.51	-1021.28	387.9362	28944.53	0.999848	0.999377				
4	28800.31	-1051.53	395.4796	28819.5	0.999848	0.999334				
4.5	28639.85	-1088.4	401.6199	28660.52	0.999848	0.999279				
5	28439.64	-1123.08	405.6814	28461.81	0.999848	0.999221				
5.5	28211.7	-1148.55	408.4393	28235.07	0.999848	0.999172				
6	27988.09	-1157.22	410.1013	28012	0.999848	0.999146				
6.5	27795.07	-1145.87	411.4811	27818.68	0.999848	0.999151				
7	27654.43	-1120.16	413.9822	27677.11	0.999848	0.999181				
7.5	27563.77	-1090.77	419.6635	27585.34	0.999848	0.999218				
8	27505.62	-1068.38	428.5179	27526.36	0.999848	0.999246				
8.5	27452.35	-1056.77	439.9659	27472.68	0.999848	0.99926				
9	27380.69	-1058.79	450.1733	27401.15	0.999848	0.999253				
9.5	27279.12	-1071.29	457.0512	27300.15	0.999848	0.99923				
10	27148.01	-1088.8	458.7437	27169.83	0.999848	0.999197				
10.5	26998.25	-1106.1	455.9505	27020.9	0.999848	0.999162				
11	26844.32	-1117.77	448.9875	26867.58	0.999848	0.999134				
11.5	26701.39	-1121.2	439.4236	26724.92	0.999848	0.99912				
12	26579.39	-1117.07	429.7309	26602.85	0.999848	0.999118				
12.5	26480.85	-1107.76	421.3587	26504.01	0.999848	0.999126				
13	26401.82	-1097.38	415.7506	26424.62	0.999848	0.999137				
13.5	26334.33	-1089.86	412.7897	26356.87	0.999848	0.999145				
14	26269.86	-1086.63	411.8103	26292.32	0.999848	0.999146				

Figure 39. Force Produce by the Simulation

When the result from various simulation is obtained, the average force for each parameter inserted during simulation is able to be seen. These force value produced by the simulation is useful to be analyzed later.

Table 6 Summary Result for running simulation.

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

4.4. 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 parameters, force directions, and ship directions.

4.4.1 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.

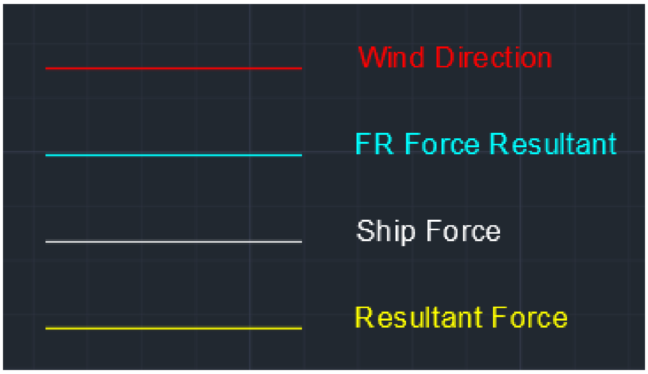


Figure 40. Line Description

Now these lines represent these following data that previously obtained from resistance calculation and flettner rotor simulation.

- Ship Force (Resistance) = 142.7 kn toward x+ direction
- Force Resultant = Based on the simulation result
- Wind Direction = - Starboard Side F: 0°;15°;30°;45°;60°;75°;90°;
  - Starboard Side B: 105°;120°;135°;150°;165°;180°
  - Port Side F: 0°;15°;30°;45°;60°;75°;90°;
  - Port Side B: 105°;120°;135°;150°;165°;180°

4.4.2 Drawing the Line

Moving on to 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.

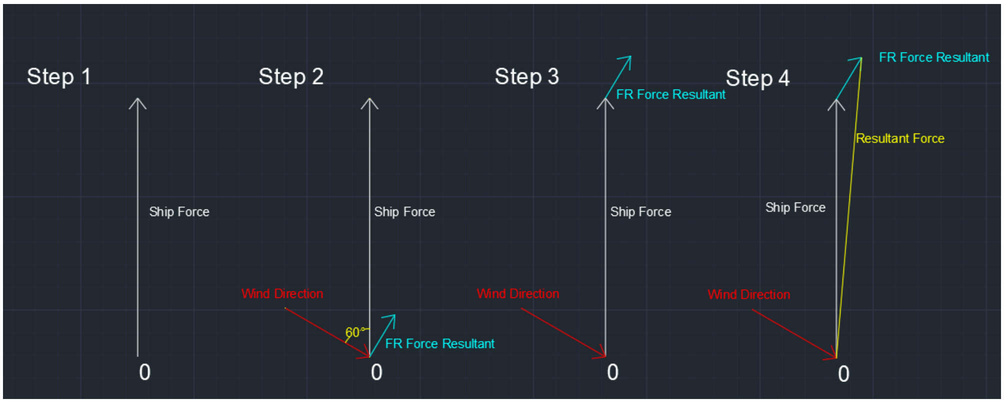


Figure 41. Step of Drawing the Line

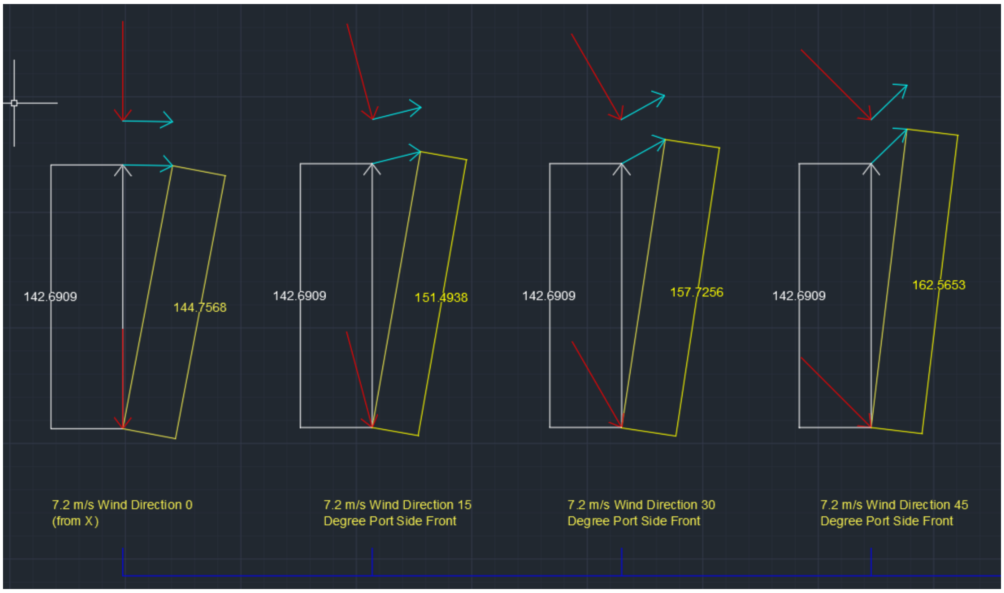


Figure 42. Variation on Wind Direction

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

4.4.3 Process Result

Based on the line vector, below the result after drawing the vector lines. The resultant force produced used to identify the new speed of the ship by using the maxsurf software.

Table 7 Starboard Side 1/2

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

Table 8 Starboard Side 2/2

Starboard Side							
Wind Speed	Ship Speed	Direction (Degree)	Ship Resis	Force Resultan	Result	Speed After	Direction
m/s	Knot	°	N	N	N	kn	°
5.6	15	0	142700	16227.58036	143338	15.028	6
5.6	15	15	142700	16227.58036	139114	14.827	6
5.6	15	30	142700	16227.58036	135070	14.626	6
5.6	15	45	142700	16227.58036	131520	14.453	5
5.6	15	60	142700	16227.58036	128757	14.31	3
5.6	15	75	142700	16227.58036	127025	14.225	2
5.6	15	90	142700	16227.58036	126475	14.189	0
5.6	15	105	142700	16227.58036	127189	14.232	2
5.6	15	120	142700	16227.58036	129061	14.325	4
5.6	15	135	142700	16227.58036	131960	14.475	5
5.6	15	150	142700	16227.58036	135586	14.661	6
5.6	15	165	142700	16227.58036	139663	14.86	6
5.6	15	180	142700	16227.58036	143918	15.06	6
4.5	15	0	142700	10462.70656	142916	15.012	4
4.5	15	15	142700	10462.70656	140187	14.875	4
4.5	15	30	142700	10462.70656	137614	14.76	4
4.5	15	45	142700	10462.70656	135372	14.645	3
4.5	15	60	142700	10462.70656	133655	14.56	2
4.5	15	75	142700	10462.70656	132572	14.512	1
4.5	15	90	142700	10462.70656	132239	14.489	0
4.5	15	105	142700	10462.70656	132686	14.513	1
4.5	15	120	142700	10462.70656	133840	14.57	2
4.5	15	135	142700	10462.70656	135656	14.656	3
4.5	15	150	142700	10462.70656	137948	14.772	4
4.5	15	165	142700	10462.70656	140553	14.893	4
4.5	15	180	142700	10462.70656	143282	15.025	4
2.7	15	0	142700	3760.436269	142693	14.98	2
2.7	15	15	142700	3760.436269	141710	14.959	1
2.7	15	30	142700	3760.436269	140809	14.91	1
2.7	15	45	142700	3760.436269	140022	14.86	1
2.7	15	60	142700	3760.436269	139432	14.845	1
2.7	15	75	142700	3760.436269	139061	14.825	0
2.7	15	90	142700	3760.436269	138949	14.821	0
2.7	15	105	142700	3760.436269	139098	14.827	0
2.7	15	120	142700	3760.436269	139489	14.848	1
2.7	15	135	142700	3760.436269	140129	14.875	1
2.7	15	150	142700	3760.436269	140914	14.918	1
2.7	15	165	142700	3760.436269	141854	14.967	1
2.7	15	180	142700	3760.436269	142814	15.01	2

Table 9 Port Side 1/2

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

Table 10 Port Side 2/2

Port Side							
Wind Speed	Ship Speed	Direction (Degree)	Ship Resis	Force Resultan	Result	Speed After	Direction
m/s	Knot	°	N	N	N	kn	°
5.6	15	0	142700	16227.58036	143338	15.028	6
5.6	15	15	142700	16227.58036	147478	15.225	6
5.6	15	30	142700	16227.58036	151235	15.4	5
5.6	15	45	142700	16227.58036	154414	15.548	4
5.6	15	60	142700	16227.58036	156832	15.659	3
5.6	15	75	142700	16227.58036	158361	15.71	2
5.6	15	90	142700	16227.58036	158924	15.75	0
5.6	15	105	142700	16227.58036	158493	15.725	1
5.6	15	120	142700	16227.58036	157089	15.6	3
5.6	15	135	142700	16227.58036	154783	15.56	4
5.6	15	150	142700	16227.58036	151686	15.417	5
5.6	15	165	142700	16227.58036	147996	15.24	6
5.6	15	180	142700	16227.58036	143918	15.06	6
4.5	15	0	142700	10462.70656	142910	15.01	4
4.5	15	15	142700	10462.70656	145595	15.135	4
4.5	15	30	142700	10462.70656	148055	15.25	4
4.5	15	45	142700	10462.70656	150156	15.35	3
4.5	15	60	142700	10462.70656	151763	15.421	2
4.5	15	75	142700	10462.70656	152793	15.466	1
4.5	15	90	142700	10462.70656	153160	15.488	0
4.5	15	105	142700	10462.70656	152872	15.475	1
4.5	15	120	142700	10462.70656	151934	15.423	2
4.5	15	135	142700	10462.70656	150400	15.362	3
4.5	15	150	142700	10462.70656	148349	15.267	3
4.5	15	165	142700	10462.70656	145929	15.155	4
4.5	15	180	142700	10462.70656	143264	15.025	4
2.7	15	0	142700	3760.436269	142693	14.98	2
2.7	15	15	142700	3760.436269	143665	15.04	1
2.7	15	30	142700	3760.436269	144561	15.087	1
2.7	15	45	142700	3760.436269	145337	15.125	1
2.7	15	60	142700	3760.436269	145936	15.156	1
2.7	15	75	142700	3760.436269	146318	15.17	0
2.7	15	90	142700	3760.436269	146459	15.175	0
2.7	15	105	142700	3760.436269	146356	15.171	0
2.7	15	120	142700	3760.436269	146000	15.16	1
2.7	15	135	142700	3760.436269	145440	15.15	1
2.7	15	150	142700	3760.436269	144662	15.09	1
2.7	15	165	142700	3760.436269	143798	15.051	1
2.7	15	180	142700	3760.436269	142814	15.01	2

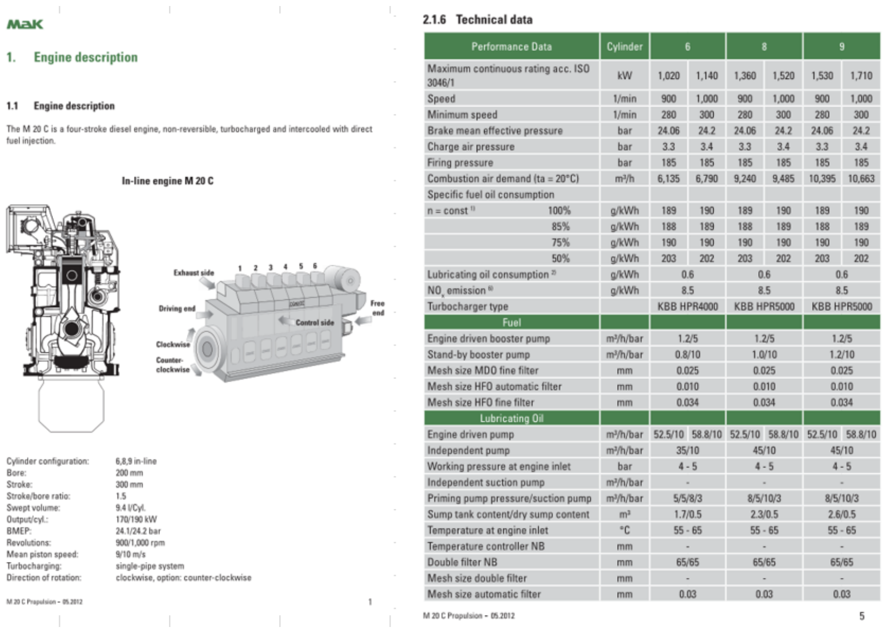
Based on the table above, the best wind direction for the flettner rotor on this project is at 90° from the port side, producing the biggest resultant force which resulting in the rising of ship's speed.

4.5 Energy Efficiency Calculation

Now in this energy efficiency calculation step, 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. The first step is to collect or gather all the data that has been calculated and determine and adding some additional data to complete the process of calculation

4.5.1 Data Collection

Since it will calculate the fuel consumption of the main engine & auxiliary engine, these two engines data are needed. For the main engine, It has already calculated and the engine that will be used is MaK Caterpillar engine with the capacity of 1140 kW and SFOC 190 g/kWHour.



MaK

1. Engine description

1.1 Engine description

The M 20 C is a four-stroke diesel engine, non-reversible, turbocharged and intercooled with direct fuel injection.

In-line engine M 20 C

Cylinder configuration:	6,8,9 in-line
Bore:	200 mm
Stroke:	300 mm
Stroke/bore ratio:	1.5
Swept volume:	9.4 l/Cyl.
Output/cyl.:	170/190 kW
BMEP:	24.1/24.2 bar
Revolutions:	900/1,000 rpm
Mean piston speed:	9/10 m/s
Turbocharging:	single-pipe system
Direction of rotation:	clockwise, option: counter-clockwise

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2.1.6 Technical data

Performance Data		Cylinder	6		8		9	
Maximum continuous rating acc. ISO 3046/1		kW	1,020	1,140	1,360	1,520	1,530	1,710
Speed		1/min	900	1,000	900	1,000	900	1,000
Minimum speed		1/min	280	300	280	300	280	300
Brake mean effective pressure		bar	24.06	24.2	24.06	24.2	24.06	24.2
Charge air pressure		bar	3.3	3.4	3.3	3.4	3.3	3.4
Firing pressure		bar	185	185	185	185	185	185
Combustion air demand (ta = 20°C)		m³/h	6,135	6,790	9,240	9,485	10,395	10,663
Specific fuel oil consumption								
n = const [1]	100%	g/kWh	189	190	189	190	189	190
	85%	g/kWh	188	189	188	189	188	189
	75%	g/kWh	190	190	190	190	190	190
	50%	g/kWh	203	202	203	202	203	202
Lubricating oil consumption [2]		g/kWh	0.6		0.6		0.6	
NO_x emission [6]		g/kWh	8.5		8.5		8.5	
Turbocharger type			KBB HPR4000		KBB HPR5000		KBB HPR5000	
Fuel								
Engine driven booster pump		m³/h/bar	1.2/5		1.2/5		1.2/5	
Stand-by booster pump		m³/h/bar	0.8/10		1.0/10		1.2/10	
Mesh size MDO fine filter		mm	0.025		0.025		0.025	
Mesh size HFO automatic filter		mm	0.010		0.010		0.010	
Mesh size HFO fine filter		mm	0.034		0.034		0.034	
Lubricating Oil								
Engine driven pump		m³/h/bar	52.5/10	58.8/10	52.5/10	58.8/10	52.5/10	58.8/10
Independent pump		m³/h/bar	35/10		45/10		45/10	
Working pressure at engine inlet		bar	4 - 5		4 - 5		4 - 5	
Independent suction pump		m³/h/bar	-		-		-	
Priming pump pressure/suction pump		m³/h/bar	5/5/8/3		8/5/10/3		8/5/10/3	
Sump tank content/dry sump content		m³	1.7/0.5		2.3/0.5		2.6/0.5	
Temperature at engine inlet		°C	55 - 65		55 - 65		55 - 65	
Temperature controller NB		mm	-		-		-	
Double filter NB		mm	65/65		65/65		65/65	
Mesh size double filter		mm	-		-		-	
Mesh size automatic filter		mm	0.03		0.03		0.03	

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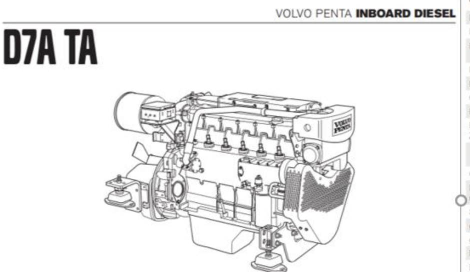
Figure 43. Main Engine Data



Technical Data

Engine designation	D7A TA		
No. of cylinders and configuration	in-line 6		
Method of operation	4-stroke, direct-injected, turbocharged diesel engine with aftercooler		
Bore/stroke, mm (in.)	108 (4.25)/130 (5.12)		
Displacement, l (in³)	7.15 (436)		
Compression ratio	17.6:1		
Dry weight bobtail, kg (lb)	690 (1521)		
Dry weight with reverse gear ZF280, kg (lb)	760 (1676)		
	Rating 2 2300 rpm	Rating 1 2300 rpm	Rating 1 1900 rpm
Crankshaft power, kW (hp)	174 (237)	148 (201)	130 (177)
Max. torque, Nm (lbf.ft) @ 1500 rpm	809 (596)	688 (507)	688 (507)
Specific fuel consumption,			
g/kWh (lb/hph) @ 2300 rpm	226 (0.366)	229 (0.371)	
g/kWh (lb/hph) @ 1900 rpm			213 (0.345)
Recommended fuel to conform to	ASTM-D975 1-D & 2-D, EN 590 or JIS KK 2204		
Emission compliance	IMO NOx, EU IWW, CCNR2		

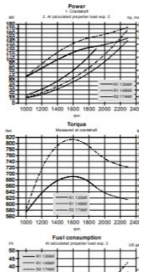


Figure 44. Auxiliary Engine Data

For the auxiliary engine it will be assumed that the auxiliary engine power is 15% from its main engine power capacity which is 171 kW. The engine that will be used for auxiliary engine is Volvo Penta D7A TA with SFOC 226 g/kWHour.. The other data such as ship speed with and without the flettner rotor, flettner rotor power consumptions already determined and for the distance, it will be varied between 500-2500 km.

4.5.2 Calculation Process

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:

$$\mathbf{t}(hour) = \frac{d\ (km)}{v(km/h)} \tag{10}$$

Where,

t = time (hour)

d = distance (km)

v = velocity (km/h)

For Example:

d = 2500 (km)

v = 27.78 (km/h)

$$\mathbf{t}(hour) = \frac{2500\ \mathbf{(}km\mathbf{)}}{27.8(km/h)} \qquad (10)$$

t = 89.9 (hour)

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

$$\mathrm{m}(kg) = \frac{t\ (hour)\ \times M/E(kW) \times ME\ SFOC\ (\frac{g}{kWH})}{(1000)} \qquad (11)$$

Where,

t = time (hour)

M/E = Main Engine Power (kW)

ME SFOC (g/kWH) = Main Engine Specific Fuel Oil Consumption

For example,

t = 89.9 (Hours)

M/E = 1140 (kW)

SFOC = 190 (g/kWH)

$$\mathrm{m}(kg) = \frac{89.9\ (hour)\ \times 1140\ (kW) \times 190\ (\frac{g}{kWH})}{(1000)} \qquad (11)$$

m = 19492.44 kg

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

$$\text{m}(kg) = \frac{t\ (hour)\ \times A/E(kW) \times AESFOC\ (\frac{g}{kWH})}{(1000)} \qquad (12)$$

Where,

t = time (hour)

A/E= Main Engine Power (kW)

AE SFOC = Auxiliary Engine Specific Fuel Oil Consumption (g/kWH)

For example,

t = 89.9 (Hours)

A/E= 174 (kW)

SFOC = 226 (g/kWH)

$$\text{m}(kg) = \frac{89.9\ (hour)\ \times 174\ (kW) \times 226\ (\frac{g}{kWH})}{(1000)} \qquad (11)$$

m = 3538.8768 kg

Total = m main engine (kg) + m auxiliary engine (kg)

= 19492.44 kg + 3538.8768 kg

= 23031.3 kg

Total Consumption during normal operation is 23031.3 kg .

Now, the second step on this process is to calculate the time taken for a voyage with a flettner rotor. It will be calculated by using the formula:

$$\mathrm{t}(hour) = \frac{d\ (km)}{v(km/h)} \qquad (10)$$

Where,

t = time (hour)

d = distance (km)

v = velocity (km/h)

For Example:

d = 2500 (km)

v = 30.046 (km/h)

$$\mathrm{t}(hour) = \frac{2500\ (km)}{30.046(km/h)} \qquad (10)$$

t = 83.2 (hour)

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

$$\mathrm{m}(kg) = \frac{t\ (hour)\ \times M/E(kW) \times ME\ SFOC\ (\frac{g}{kWH})}{(1000)} \qquad (11)$$

Where,

t = time (hour)

M/E = Main Engine Power (kW)

ME SFOC (g/kWH) = Main Engine Specific Fuel Oil Consumption

For example,

t = 83.2 (Hours)

M/E = 1140 (kW)

SFOC = 190 (g/kWH)

$$\mathrm{m}(kg) = \frac{83.2\ (hour)\ \times 1140\ (kW) \times 190\ (\frac{g}{kWH})}{(1000)} \qquad (11)$$

m = 18021.886 kg

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

$$\mathrm{m}(kg) = \frac{t\ (hour)\ \times A/E(kW) \times AESFOC\ (\frac{g}{kWH})}{(1000)} \qquad (12)$$

Where,

t = time (hour)

A/E= Main Engine Power (kW)

AE SFOC = Auxiliary Engine Specific Fuel Oil Consumption (g/kWH)

For example,

t = 83.2 (Hours)

A/E= 174 (kW)

SFOC = 226 (g/kWH)

$$\mathrm{m}(kg) = \frac{83.2\ (hour)\ \times 174\ (kW) \times 226\ (\frac{g}{kWH})}{(1000)} \qquad (11)$$

m = 3271.8906 kg

For the flettner rotor it is calculated by using the formula of auxiliary engine since the rotor power load will be loaded to auxiliary engine,

$$m(kg) = \frac{t\ (hour)\ \times FR\ (kW) \times AESFOC\ (\frac{g}{kWH})}{(1000)} \qquad (12)$$

Where,

t = time (hour)

FR = Flettner Rotor Power (kW)

AE SFOC = Auxiliary Engine Specific Fuel Oil Consumption (g/kWH)

For example,

t = 83.2 (Hours)

FR = 77 (kW)

SFOC = 226 (g/kWH)

$$m(kg) = \frac{83.2\ (hour)\ \times 77.22\ (kW) \times 226\ (\frac{g}{kWH})}{(1000)} \qquad (13)$$

m = 1452.186 kg

Total = m main engine (kg) + m auxiliary engine (kg) + Flettner Rotor Consumption (kg)

= 19492.44 kg + 3271.8906 kg + 1452.186

= 22745.9 kg

Total Consumption during operation with flettner rotor is 22745.9 kg

The savings resulted based on the operation of flettner rotor is 23031.3-22745.9 equals to 285.34 kg

Now, this calculation will be varied based on the distance covered and materials being used for the rotor.

Without Flettner Rotor

No	Ship Speed (knots)	Distance (km)	Time (hour)	M/E Oil Cons. kg	A/E Oil Cons. kg	Total kg
1	15	5000	179.9856012	38984.88121	7077.75378	46062.635
2	15	2500	89.99280058	19492.4406	3538.87689	23031.317
3	15	1000	35.99712023	7796.976242	1415.550756	9212.527

4.5.3 The Result of Calculation

Table 11 Calculation without flettner rotor

Table 12 With flettner rotor distance 5000 km

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

Table 13 With flettner rotor distance 2500 km

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

Table 14 With flettner rotor distance 1000 km

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

CHAPTER V
CONCLUSION AND SUGGESTION

5.1. Research Conclusion

Based on the result of simulation, calculation and the analysis of flettner rotor on this project, 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 clock or counterclockwise.
3. The best configuration of flettner rotor to produce a good energy efficiency on this project 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.

5.2 Suggestion

1. For the future, the research can be developed to find out the material strength of the flettner rotor itself.
2. In the future, the research can be developed by simulating the flettner rotor together with the ship and see the detail effect caused by the flettner rotor installation to the ship

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ATTACHMENTS

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