Innovative Climate Change Emissions Reduction: The Cargo Ship Flettner Rotor Centrifugal Vortex Exhaust Scrubber

3D CAD MODELING USED TO DESIGN EXHAUST SCRUBBER INTO FLETTNER ROTOR GEOMETRY AND OPTIMIZED WITH COMPUTATIONAL FLUID DYNAMICS

BACKGROUND

- This is an exciting time for cargo ship naval architecture as technologies as new as AI and as old as wind power converge to reduce our transportation climate change footprint.
- Despite electrification of vehicles, optimistic attempts to "leave it in the ground," and a fossil fuel shift to plastic, petroleum fuels will be part of our lives for decades, and with it the heavy fuel oil byproducts of gasoline, diesel, and jet fuel. This dirty residual fuel is difficult to further refine and thus finds a use powering our cargo ship fleet, which are coming under increasing scrutiny as they contribute 4% to global climate change contributions. (2020 IEC rule)
- Our desire to use raw materials from around the globe or take advantage of relative efficiencies in production shows no sign of slowing, therefore our global cargo fleet consisting of over 100,000 vessels will persist.
- Engineering solutions abound, however many are costly, add complexity, and may even have unintended side effects such as reduced cargo capacity, increased maintenance, and water pollution.

OCEAN TRANSPORT TODAY

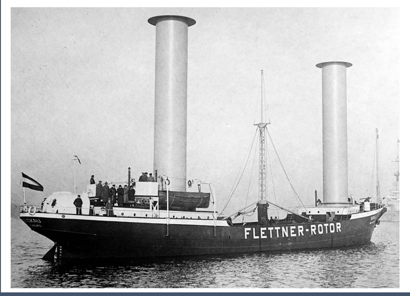
PROBLEM: Environmental improvements often mean less cargo space, increased capital and operating costs

ENGINE EXHAUST SCRUBBERS

- Land-based scrubber exhaust gas scrubbers are a well established method of cleaning emissions from oil and coal fired power generating stations.
- Typical designs rely on fans and alkaline water mist to remove particulate matter and sulphur oxides from combustion products, especially from residual fuels such as heavy fuel oil.
- Open loop scrubbers require increased energy costs to run pumps, and discharge scrubber water overboard. Closed loop scrubbers require treated water to be stored on board until discharged for treatment on land.
- Capital cost of scrubbers ranges from $500K to $5M, not including loss of capacity for drydock and retrofit, loss of cargo space, increased maintenance, or associated decrease in engine efficiency.

THE FLETTNER ROTOR

- Flettner rotors use the Magnus effect to harness wind power without setting and trimming sails. Flettner rotors generate approximately an order of magnitude more lift than sails of the same area.
- The rotor ship Baden Baden used Flettner rotors and crossed the Atlantic in 1925, however the challenges of maintaining balanced rotating steel cylinders and vessel stability was shelved until recent improvements to composite materials improved stability, and climate change concerns renewed interest in wind power for large ships.



SOLUTION: FLETTNER VORTEX SCRUBBER

A novel centrifugal vortex scrubber integrated into a Flettner rotor creates a hybrid wind and fossil fuel powered vessel that cleans exhaust while generating propulsive power, that more than compensates for the engine power loss through the scrubber, and the initial capital investment. Multiple Flettner Vortex Scrubbers would be fit to a large vessel such as a neopanamax.

Hypothesis: A novel centrifugal vortex scrubber can be integrated into a Flettner rotor to clean exhaust while generating propulsive power that more than compensates for the engine power loss through the scrubber, and the initial capital investment.

Phase I: 3D Modeling and Computational Fluid Dynamics (CFD) to Maximize Centrifugal Force and Minimize Pressure Drop
- Independent Variable: scrubber geometry
- Dependent Variables: pressure drop, maximum exhaust velocity
- Control: verification and validation of CFD model

Phase II: Flettner Rotor Prototype, 1:39 scale
- Independent Variables: rotor speed, wind speed, tack angle
- Dependent Variable: Kutta–Joukowski force generated by Flettner rotor
- Positive Controls: maximum Flettner rotor RPM and maximum wind speed
- Negative Controls: zero Flettner rotor RPM and maximum wind speed off beam, maximum Flettner rotor RPM and zero wind speed

Phase III: Testing the Vortex Exhaust Scrubber Inside the Flettner Rotor
- Independent Variable: Test duration (time)
- Dependent Variable: mass of exhaust particulate matter
- Positive Control: exhaust without scrubber
- Negative Control: engine off, no soot

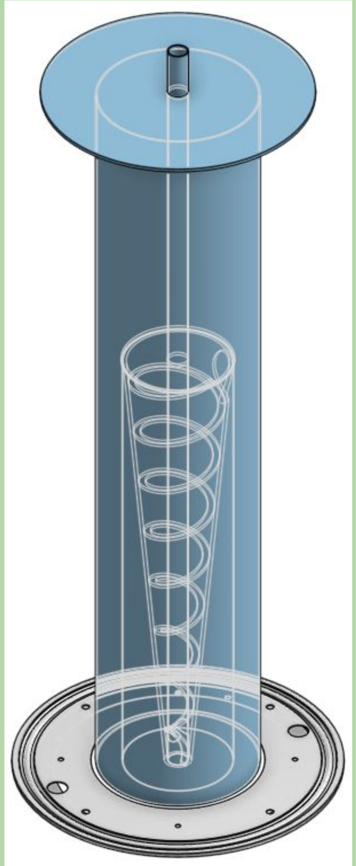
Research Questions:
1) Can a centrifugal vortex exhaust scrubber be fitted inside a typical Flettner rotor?
2) How will the scrubber affect Flettner rotor performance?
3) How will this Flettner Vortex Scrubber affect vessel performance?
4) Can an exhaust scrubber be simplified to eliminate high maintenance moving parts and water droplet system?
5) What is the pressure drop across the scrubber, indicating loss of engine power?

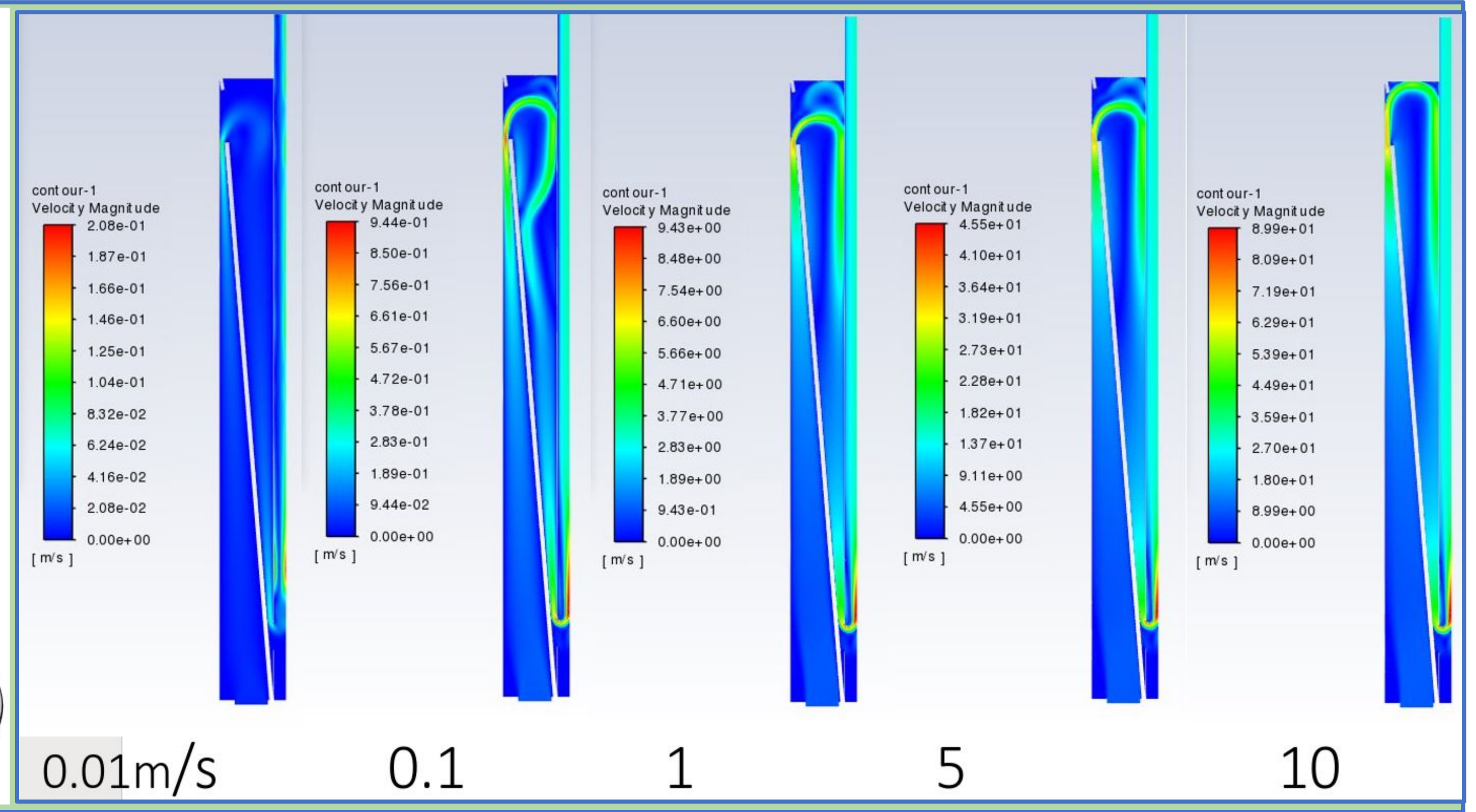
1 Design in 3D modeling to ensure fit of rotating cylinders

2 CFD to maximize centrifugal force, maximize particulate matter retained, and minimize pressure drop

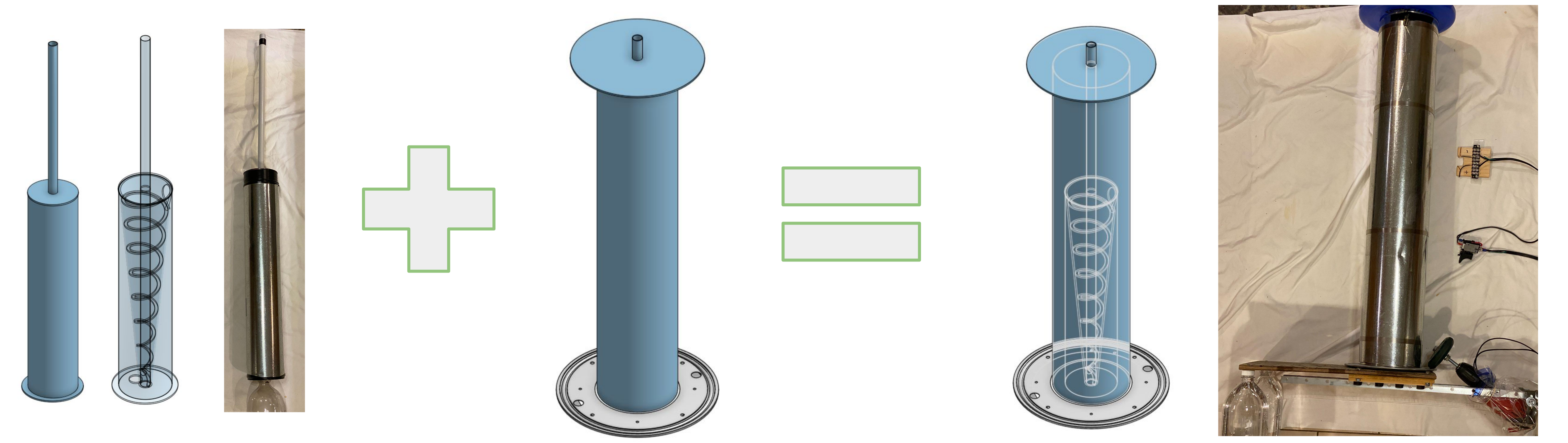
3 Refine Design and 3D model

4 Construct Prototype





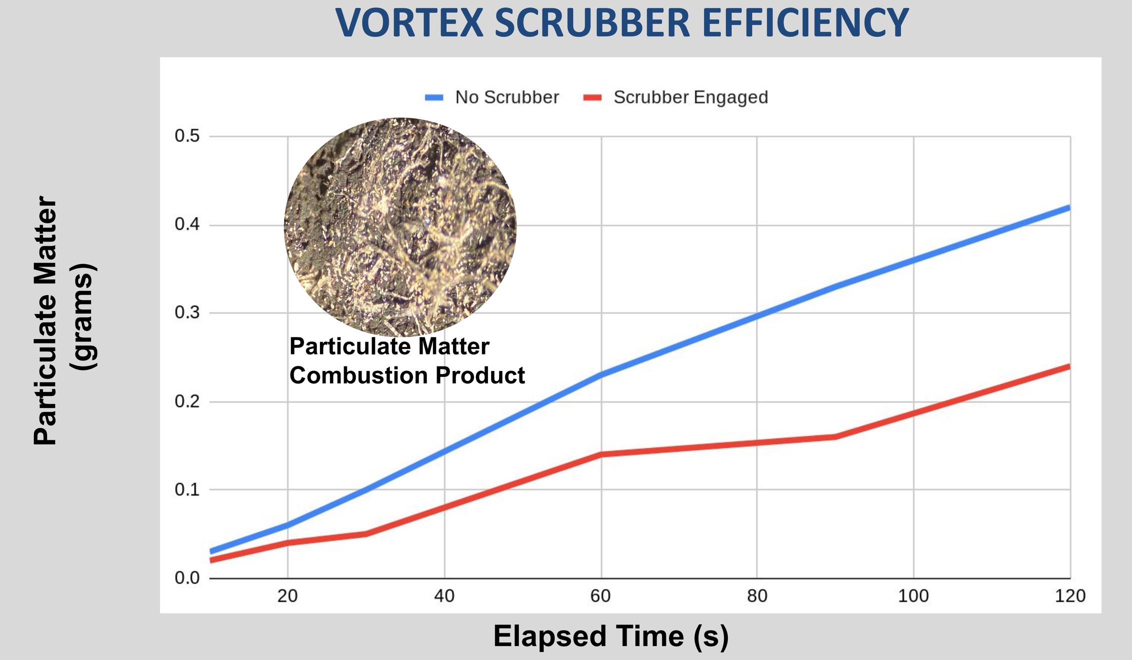
PROTOTYPE EXHAUST VORTEX SCRUBBER ASSEMBLED INTO FLETTNER ROTOR



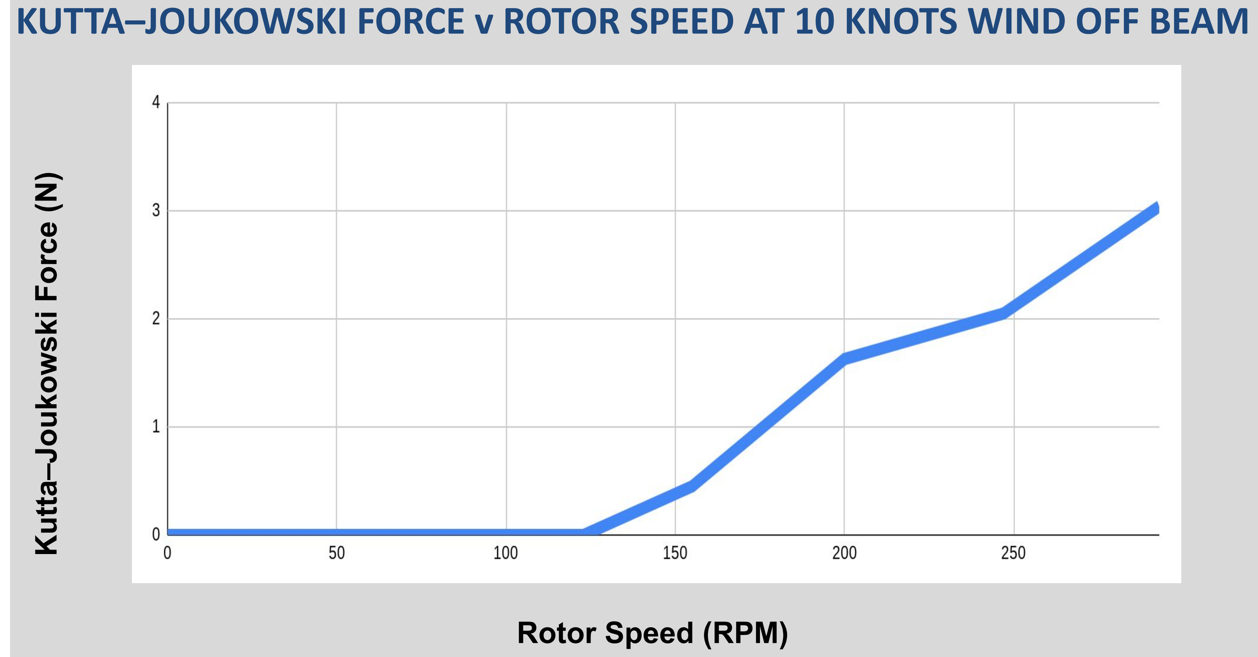
The exhaust scrubber is of low density compared to tanks or other shipboard mechanical systems, which makes it ideal to locate above the center of mass without significantly increasing the metacentric height and affecting ship stability or seakeeping.
Scrubber design is improved and optimized for shipboard deployment by replacing high maintenance moving parts with cyclonic separation geometry.
The Flettner rotor cylinder is based on a commonly used 1:6 aspect ratio. Prototype is 1:39 scale based on dimensions of readily available commercial and repurposed material.
The assembly image shows the Prototype Flettner rotor and Vortex Scrubber Assembly, drive assembly and controls, base and ballasted columns for use with water test tank and wind tunnel test stand.

RESULTS:

VORTEX SCRUBBER EFFICIENCY

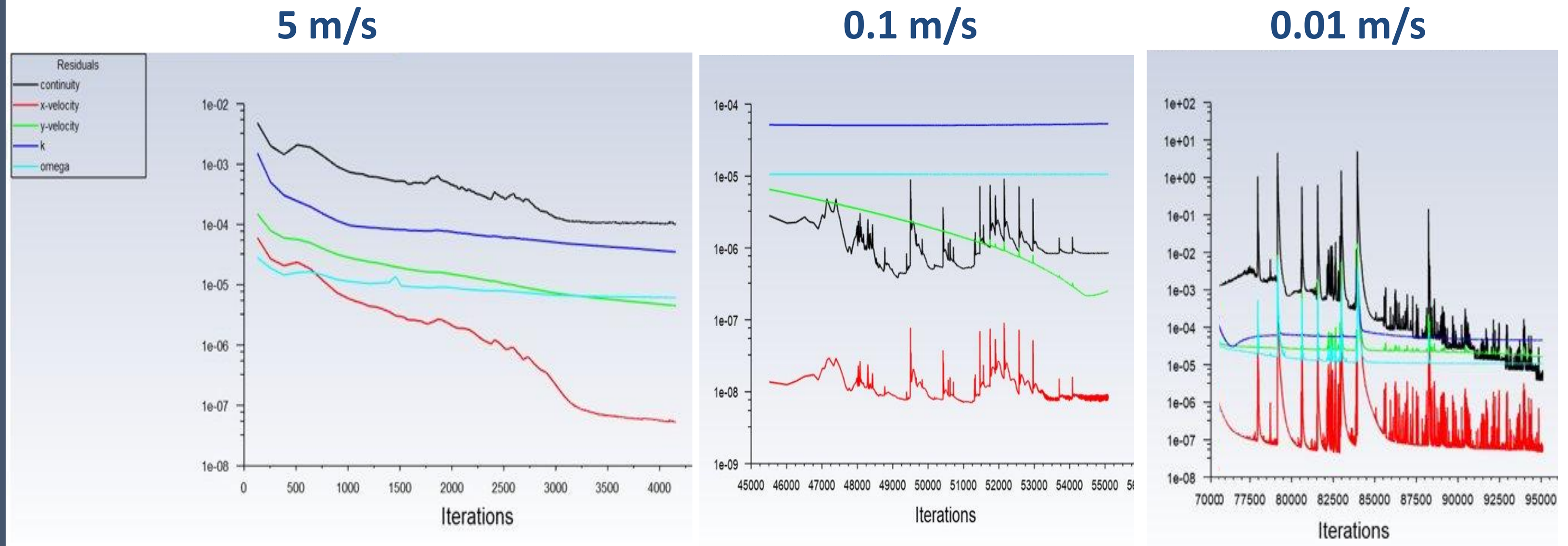


KUTTA–JOUKOWSKI FORCE v ROTOR SPEED AT 10 KNOTS WIND OFF BEAM

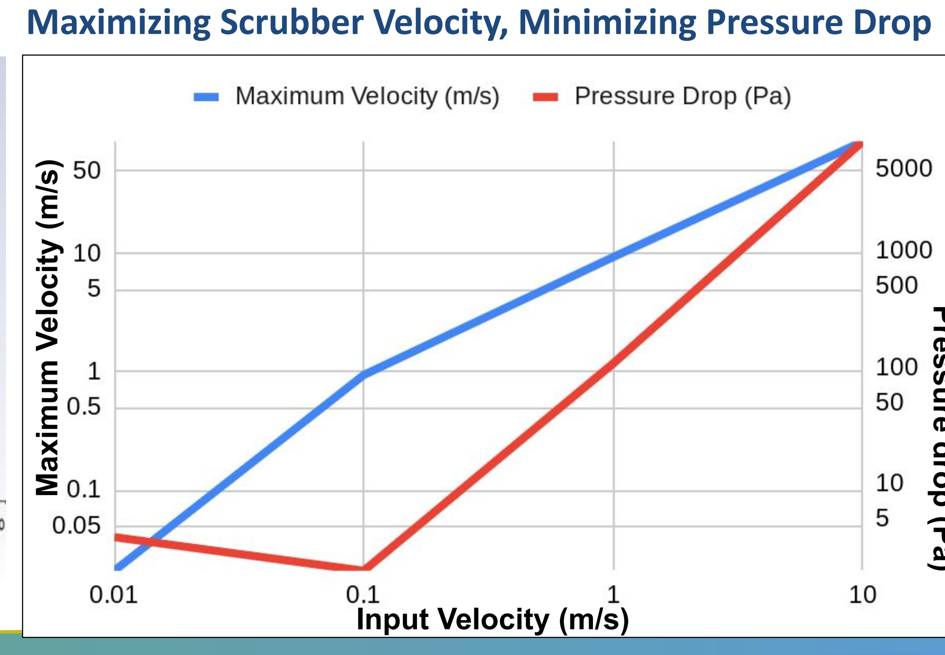


CFD Residual Plots at Three Input Velocities:

5 m/s 0.1 m/s 0.01 m/s



Maximizing Scrubber Velocity, Minimizing Pressure Drop



DATA ANALYSIS & DISCUSSION

- Computational Fluid Dynamics runs in ANSYS showed areas of laminar flow in parallel layers, as well as complex and chaotic turbulent flows. The exhaust fluid was modeled as air, which makes up the majority of exhaust mass. Mass flow imbalance residuals on the order of 10^{-8} indicate a well-converged model.
- A two dimensional CFD model running mesh with 134,000 cells and k–omega two equation turbulence model used to approximate Reynolds-averaged Navier–Stokes equations for viscous fluid flow converged around 4000 iterations with input velocity set at 5 m/s. Reducing input velocity to 0.1 m/s caused the convergence residuals to decrease in a less consistent fashion, and required about 9500 iterations to converge. Further reducing input velocity by another order of magnitude to 0.01 m/s resulted in an even less consistent residual plot, and required about 20,000 iterations to converge.
- A three dimensional CFD analysis was informative and yielded the following insight: Vortex needs to start at top of funnel. Since the engine is lower than the the rotor the exhaust enters from bottom, the space between the scrubber cylinder and the funnel can be used as an additional spiral vortex to remove particulate matter. CFD showed that more consistent performance could be achieved by adding flow guides to the inlet at the bottom of the scrubber, and the inlet at the top of the funnel for a more consistent vortex. The exhaust tube does not need to extend to the bottom of the funnel. The diameter of the funnel inlet can be decreased, and the diameter of the exhaust tube can be increased.

STATISTICAL ANALYSES:

A statistical sampling plan was designed. Multiple samples were taken at each operating point. Two-Sample t-Tests were used to compare means at each operating point.

- The null hypothesis was $\mu 1 = \mu 2$ that the scrubber did not remove exhaust particulate matter and the means are the same.
- The alternate hypothesis was that $\mu 1 < \mu 2$ that the scrubber effectively removed exhaust particulate matter and the means are different.
- For all operating points $p <$ alpha (0.05), the null is rejected and alternate accepted.

CONCLUSIONS:

This Flettner Vortex Scrubber shows promise as an economically attractive design to limit emissions from heavy fuel oil engines in marine applications, as well as provide an auxiliary propulsion source to reduce heavy fuel oil consumption, both climate change causes. Financial viability is strong.

- The 3D model, computational fluid dynamics results, and prototype test data all show that an effective centrifugal vortex exhaust scrubber can be fitted inside a typical Flettner rotor.
- Flettner rotor performance was tested in a water test tank and wind tunnel and was not affected by the presence of the scrubber.
- The exhaust scrubber was simplified to eliminate high maintenance moving parts. A cyclonic separation design worked well in the Flettner rotor geometry and effectively removed 42% of particulate matter.
- Under even mild wind conditions, the thrust generated by the Flettner rotors more than overcomes the efficiency loss of scrubber.
- A conservative estimate for Flettner rotor auxiliary power performance is the Maersk Pelican tanker's 8.2% reduction in fuel use. If this result were to scale to the global cargo shipping fleet, it would mean a climate change impact equivalent to taking five million cars off the road. Combining Flettner rotors with an exhaust scrubber will make the investment more attractive for ship owners and operators and can increase the rate of adoption of this climate change mitigation technology.

FUTURE STUDIES

- Develop a seaworthy scale prototype for testing in protected water such as a bay or harbor.
- Select materials, alloys and coatings materials. Perform fatigue analysis and accelerated lifetime testing. A valuable reference may be MIL STD 810 G methods such as 509.5 salt fog and 528.1 Mechanical Vibrations of Shipboard Equipment.
- Investigate global shipping lane weather routing for optimal Flettner rotor performance.
- Further iterate vortex design to improve efficiency.

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3D Design and modeling performed in PTC Onshape CAD software
Computational Fluid Dynamics analysis in Ansys Fluent
Statistical tests were performed in Excel Analysis ToolPak
Maersk container ship image from https://safetyatsea.net/news/2020/cargo-ship-crew-testing-positive-for-covid-19/
Exhaust image from https://www.marineinsight.com/tech/black-smoke-coming-ships-funnel-port/amp/
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