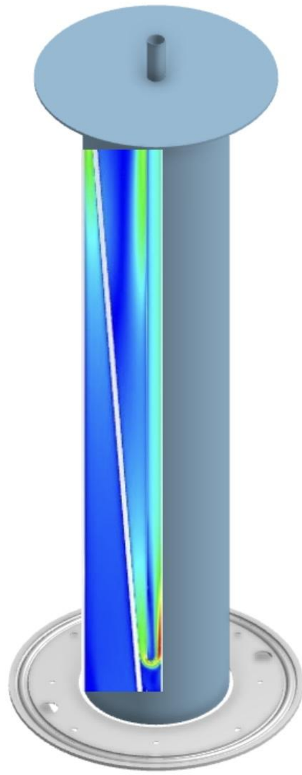
Innovative Climate Change Emissions Reduction: The Cargo Ship Flettner Rotor Centrifugal Vortex Exhaust Scrubber



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I. Abstract:

Our global cargo ship fleet is responsible for 4% of global climate change emissions as well as particulate pollutants that leads to roughly 7.6 million childhood asthma cases and 150,000 premature deaths annually. Heavy fuel oil or “bunker” is a residual product of petroleum refining for gasoline and diesel and thus unlikely to go away. Marine heavy fuel oil engines are a mature, low cost, and reliable technology. Scrubber technology is well established but costly, adds complexity, and may even have unintended side effects such as reduced cargo capacity, increased maintenance, and water pollution. 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. 3D CAD modeling, computational fluid dynamics analysis, and prototyping were used for design iterations and testing. 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 replace high maintenance moving parts with a cyclonic separation design that fits well in the Flettner rotor geometry. The scrubber removed 42% of particulate matter. Under even mild wind conditions, the Kutta–Joukowski force generated by the Flettner rotor, more than overcomes the engine efficiency loss due to pressure drop across the scrubber. 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. If conservative estimates of Flettner rotor auxiliary power performance scale to the global cargo shipping fleet, it could 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 important climate change, and public health risk mitigation technology.

II. Table of Contents:

III. Key Words: Climate Change, Cargo Ship, Air Pollution, Flettner Rotor, Exhaust Scrubber, 3D modeling, Computational Fluid Dynamics (CFD)

IV. Abbreviations and Acronyms: CFD: Computational Fluid Dynamics
IEC: International Electrotechnical Commission

1. Introduction:

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)

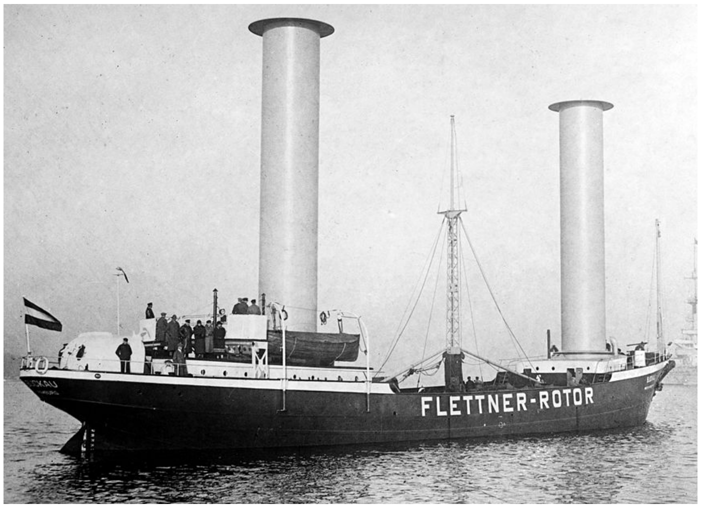
Our desire to use raw materials from around the globe or take advantage of relative efficiencies in production shows no sign of slowing, therefore our global cargo fleet consisting of over 100,000 vessels will persist.

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

Ships began using oil as an energy source around 1900, however use of exhaust scrubbers on ships was very limited until recently, due to light regulation. In 1973 the regulation of pollution in international waters was first discussed at the first marine pollution convention, or MARPOL. Sulphur emissions restrictions did not go into effect until 2012 with a 3.5% sulfur cap. In 2020 this cap was reduced to 0.5%, prompting ships to either consume less residual fuels, or install scrubbers. Because of this, it seems like scrubber technology is designed around land-based applications like power generating stations that have been more regulated, and not marine applications. Heavy fuel oil is a residual product of petroleum refining for gasoline and diesel. Marine fuel oil engines are a mature, low cost, and reliable technology. Marine exhaust scrubbers and cargo ship wind power are very important technologies to advance. Large ships contribute to 4% of global climate change emissions. According to the Yale School of the Environment, we are just learning that the combustion products of heavy fuel oil are especially noxious pollutants which can travel hundreds of miles leading to roughly 7.6 million childhood asthma cases and 150,000 premature deaths annually.

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.

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. ships.



The solution developed here is the 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.

This research hypothesized that 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. In phase I, 3D modeling was used to design an exhaust scrubber into a typical Flettner rotor geometry, and the geometry was optimized with Computational Fluid Dynamics (CFD) to maximize exhaust velocity and the amount of particles removed, and minimize the power-draining pressure drop. The scrubber geometry was the independent variable. The dependent variables were pressure drop and maximum exhaust velocity. The control was the verification and validation of the CFD model. In Phase II. the 1:39 scale Flettner rotor prototype was evaluated. The independent variables were rotor speed, wind speed, tack angle. The dependent variable was the Kutta–Joukowski force generated by Flettner rotor that would propel the ship. The positive control was the Flettner rotor set at maximum RPM and exposed to maximum wind speed. There negative controls were: zero Flettner rotor RPM and maximum wind speed off beam, maximum Flettner rotor RPM and zero wind speed. In Phase III the Vortex Exhaust Scrubber inside the Flettner rotor was tested. The independent variable was the test duration time, and the dependent variable was the mass of the exhaust particulate matter. The positive control was exhaust that had not been run through the scrubber. The negative control was running with the simulation engine off and no soot picked up. The research questions explored here were: 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 the 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?

2. Materials and Methods:

2.1 Risk and Safety: Personal protective equipment was be used: latex gloves, safety glasses, masks, hearing protection, carving gloves, utility gloves to protect from sharp edges. Safety disconnects and Ground Fault Current Interrupts will be installed.

2.2 3D Modeling: 3D modeling was used to design an exhaust scrubber into a Flettner rotor geometry. Onshape was the software used for 3D modeling design to ensure the fit of the rotating cylinders. In addition to documenting the design, 3D modeling was a great design tool to use to ensure proper fit of rotating cylinders.

2.3 CFD: Computational Fluid Dynamics was used to optimize the 3D modeling. ANSYS was utilized as the software. CFD was used to maximize the centrifugal force, maximize particulate matter retained, and minimize pressure drop. CFD was run on viscous flow with density held constant. Design was refined and iterated based on CFD analysis results to optimize the exhaust scrubber geometry. CFD required adapting the 3D model for computational fluid dynamics by defeaturing and creating a domain boundary. Next a mesh for finite element analysis was developed. The k–omega two equation turbulence model as an appropriate balance of resolution and complexity. This model is used to approximate Reynolds-averaged Navier–Stokes equations for viscous fluid flow.

Running various input conditions and monitoring the pressure drop across the scrubber as well as the maximum velocity was informative about the behavior of exhaust gas within the scrubber. Running as an injection in a discrete phase model to track the behavior of exhaust particulate matter helped make further optimizations. Overall the process required improving and iterating exhaust scrubber geometry to maximize centrifugal force, maximize particulate matter retained, and minimize pressure drop.

2.4 Prototype Assembly: An exhaust scrubber was constructed utilizing space inside the 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. The 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. The prototype is 1:39 scale based on dimensions of readily available commercial and repurposed material. The assembly comprised the prototype Flettner rotor and vortex scrubber assembly, drive assembly and controls, base and ballasted columns for use with the water tank and wind tunnel test stand.

For prototype constructions, components were repurposed whenever possible. First various scrap hardware were disassembled for parts, such as computers, garage door openers, etc. A broken hand drill was disassembled. The motor was removed. Wires were unsoldered and labeled. A power supply was connected to the controls with 16 gage wire, and the motor was reconnected with splices.

The drive for the Flettner rotor in the prototype required an appropriate speed and torque to be applied in such a way to limit horizontal loading on the ball bearing turntable. The drive was constructed from a broken hand drill redesigning to power a polyurethane wheel that exerted a vertical force on the turntable instead of a horizontal force. This also made it easy to disengage the drive mechanism and let the Flettner Rotor spin freely.

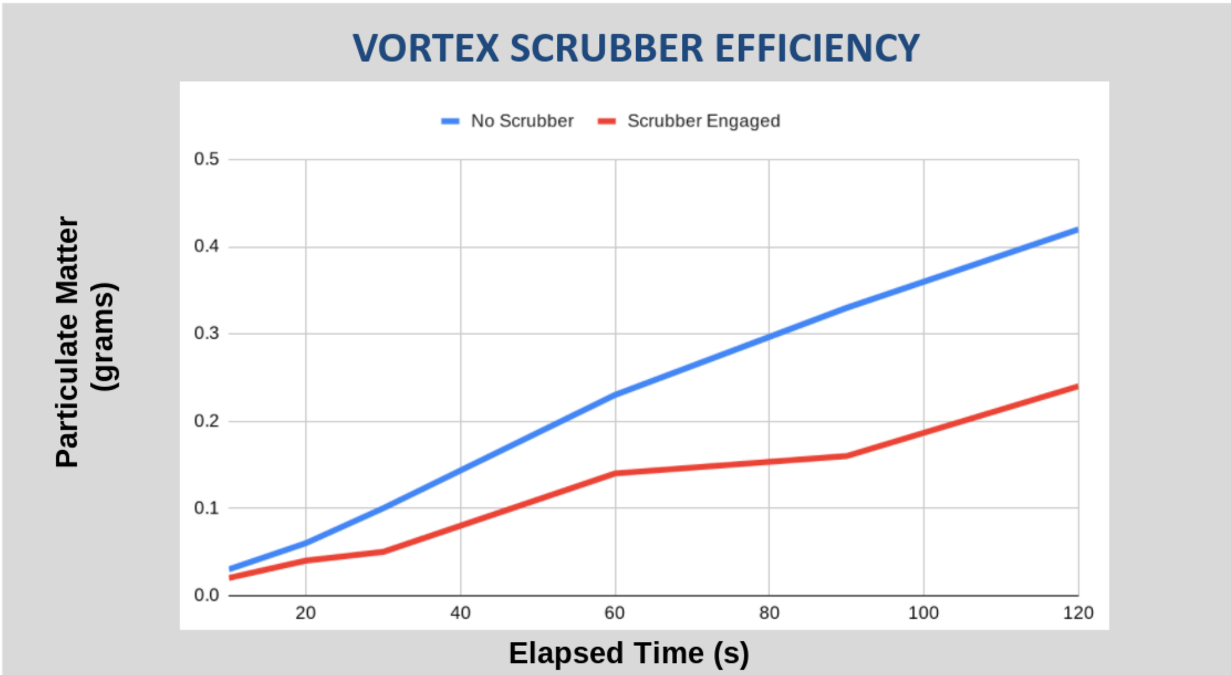
Commercial machine components were specified where repurposed material could not be identified, e.g. ball bearing turntable. The scrubber cylinder and Flettner rotor cylinder were constructed and modified from lightweight gage HVAC galvanized steel 4” round duct. The bottom end was closed with a 4” diameter steel coffee can, which worked well as it was already engineered for a maximum strength to weight ratio.

2.5 Wind Tunnel Test Stand: A wind tunnel was constructed and wind speed was measured with an anemometer and verified to be 10 knots. Wind was positioned directly off the beam of the prototype while it was floated in the test tank. The rotor speed was adjusted and measured with a tachometer. The Kutta–Joukowski Force was measured with a precise force sensor. Wind angle was adjusted and measured with a modified protractor.

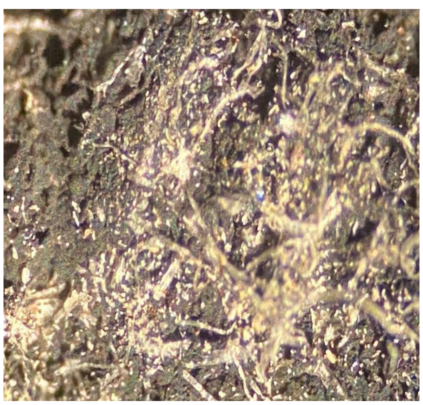
2.6 Testing Exhaust Scrubber: The Scrubber Efficiency Test Stand used a purpose-built lantern to simulate the sub-micron particulate in heavy fuel oil engine exhaust. It was made from a pickled herring jar with holes cut in the lid. A thick cotton wick was woven and extended for incomplete combustion. A frame was built from scrap wood, 3” construction screws, and 1.25” drywall screws. Flanges from a pool ladder were cleaned and used to hold the test filter media. The scrubber prototype was secured upright. A hood was connected to the inlet at the bottom of the scrubber above the lantern, and a vacuum assembly was used to draw air and combustion products through the scrubber and through a test filter media. The vacuum assembly was controlled using a remote switch and GFCI and ran for the designated test duration. The contaminated filter was removed and massed after tare.

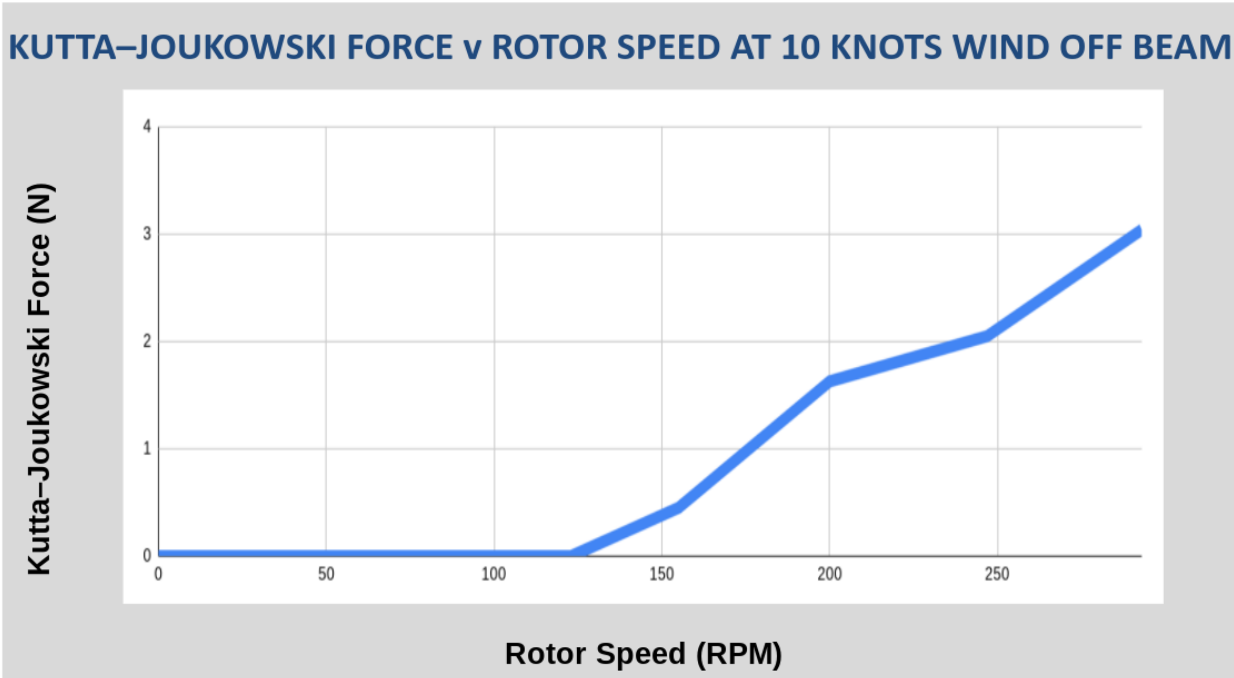
2.7 Microscopy: Microscopy was used to visualize the carbon clusters emitted by the combustion process and better understand their properties.The filter after combustion was viewed to observe how the particles were being captured in the fiber.

3. Results:

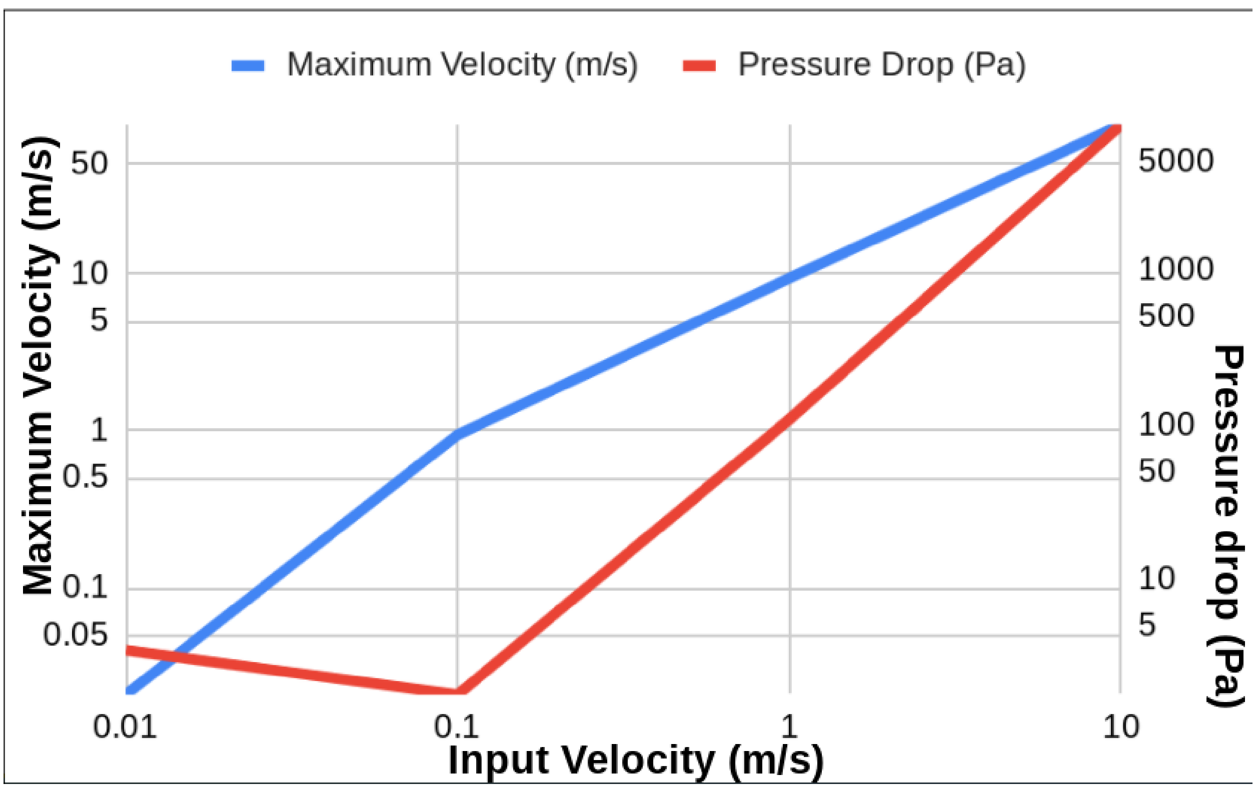


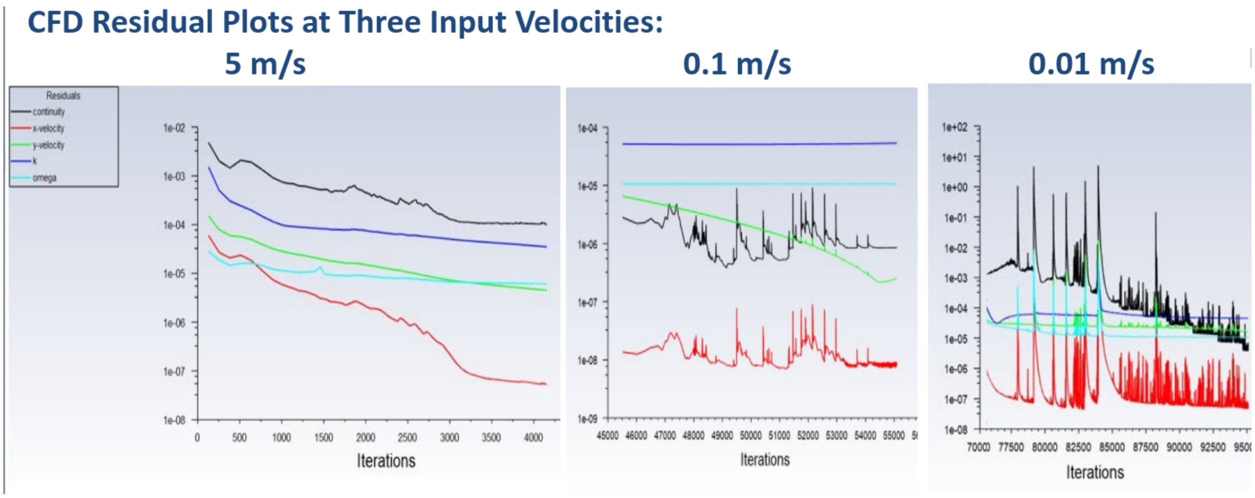
Particulate Matter Combustion Product





Maximizing Scrubber Velocity, Minimizing Pressure Drop





4. 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 material. 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.

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 $\mu1 = \mu2$ that the scrubber did not remove exhaust particulate matter and the means are the same.
The alternate hypothesis was that $\mu1 < \mu2$ 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.

5. 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 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, however this is less than the 99% removal rate advertised by commercial scrubber manufacturers.
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.

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