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CENTRIFUGAL NUCLEAR THERMAL ROCKET CHALLENGES AND POTENTIAL

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The Centrifugal Nuclear Thermal Rocket (CNTR) is a liquid fueled fission propulsion concept designed to heat propellant to 5000 K prior to expansion through a nozzle. A specific impulse up to 1800 s may be achieved using hydrogen propellant, and a specific impulse up to 1000 s may be achieved using more storable propellants such as methane, ammonia, or propane. The high uranium density of the liquid metallic uranium or liquid uranium carbide fuel will help enable compact engines suitable for missions such as fast (<15 month) round trip human Mars missions or high delta-V missions in cislunar space. Long term applications of the CNTR could include the advanced exploration and utilization of the solar system through direct use of in-situ volatiles as propellant.

Challenges associated with the CNTR are numerous. Centrifugal force is used to retain the liquid fuel in rotating fuel cylinders, and rotational velocities up to 5000 rpm may be required. Propellant flow must be directed such that all structures and moderators in the core are adequately cooled prior to the propellant entering the liquid fuel and being heated to 5000 K. The rotating fuel cylinder wall (RFCW) must have an inner surface designed to be compatible with liquid uranium metal or uranium carbide fuel up to at least 1500 K, and that inner surface may also need to be textured to help maintain acceptable wall temperatures. Propellant must flow radially inward through the RFCW while fuel is simultaneously contained. The RFCW should ideally be made from a material with low neutron absorption to help minimize engine mass and facilitate the use of High Assay Low Enriched Uranium (HALEU) fuel in the system. The drive system for the rotating fuel cylinders must support all phases of operation.

This paper will discuss computational and experimental research being conducted to address some of the challenges associated with the CNTR, and will also note potential mission benefits from the CNTR.

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INTRODUCTION

The potential for using fission energy in rocket propulsion was first proposed soon after the discovery of fission itself. Significant studies began in 1946, and from 1955 through 1973 extensive development was performed on solid fuel nuclear thermal propulsion systems with an upper performance limit of 875 s Isp for the axial flow, solid fuel Rover/NERVA style engine. In the 1960s some research related to liquid fuel and gas core nuclear rockets was also performed, with an upper performance limit of 2000 s Isp typically assumed for liquid fueled systems (using hydrogen propellant) and an upper limit of 3000 to 5000 s Isp typically assumed for gas core systems. Significant additional work on solid fuel nuclear thermal propulsion (NTP) systems was performed under the Timberwind/SNTP program (1987 – 1993), and during that time liquid fuel and gas core systems were also revisited as part of the Space Exploration Initiative.

All fission systems have the attribute of essentially unlimited energy density in the fissile fuel. The fact that the fission reaction can be self-sustaining without any need for drivers, chemical reactions, etc. also adds design flexibility. However, as shown in a recent paper by Laube et al.[1] the fact that a propulsion system is "nuclear" does not in and of itself guarantee that it will be capable of performing certain missions or have significant advantages over traditional propulsion systems. Although similar technologies can be used for a variety of nuclear engine designs, the specific engine design must be optimized for a given application to ensure the engine provides the most significant mission advantage possible.

The Centrifugal Nuclear Thermal Rocket (CNTR) is a liquid fueled nuclear thermal propulsion system designed to heat a propellant to 5000 K prior to expansion through a nozzle. The corresponding performance is an Isp up to 1800 s with hydrogen and up to 1000 s with more storable propellants such as methane, ammonia, or propane. The CNTR reactor configuration is similar to the reactor configuration baselined in the Timberwind/SNTP program, with the notable exception being the use of liquid fuel contained in rotating fuel cylinders instead of solid (coated particle) fuel contained in stationary fuel cylinders. Outside of the fuel cylinders very similar (often identical) technologies can be used as operating temperatures would be similar in most other areas of the reactor and engine. In addition, because the CNTR is designed for in-space use only, power densities within the system will be significantly less than those required by the Timberwind/SNTP system. Details of the Timberwind/SNTP program are given in (3).

A notional schematic of a 19 fuel cylinder CNTR is shown in Figure 1, and a notional schematic with additional components labeled is shown is Figure 2, where each fuel cylinder will hereafter be referred to as a Centrifugal Fuel Element (CFE). Design optimizations performed by Penn State University[2] indicate that a reactor mass below 1000 kg is achievable. Total engine mass will be higher, and optimization of turbines and mechanisms for rotating the CFEs will be important.

Before discussing the numerous challenges associated with the CNTR, it is important to note the potential benefits that may make overcoming the challenges worthwhile. First, the potential for very high Isp (up to 1800 s) with hydrogen could help make human Mars missions a reality by reducing total required crew time away from earth from >30 months to <15 months. The ability to achieve high Isp (up to 1000 s) with more storable propellants would add flexibility to Mars mission planning (may facilitate pre-deploying return propellant at Mars) and would also benefit cislunar applications where long periods of in-space dormancy may be desired along with the ability to efficiently use high density propellants. The CNTR will also enable direct trajectory scientific missions to the outer planets, where no planetary gravity assists are needed which opens up more frequent launch windows and allows significantly shorter transit times. Missions have been modeled for a 2.2 metric ton scientific spacecraft launched aboard a Vulcan Heavy launch vehicle, requiring only 16 months for a Jupiter rendezvous mission and 7.4 years for a Uranus rendezvous mission[4].

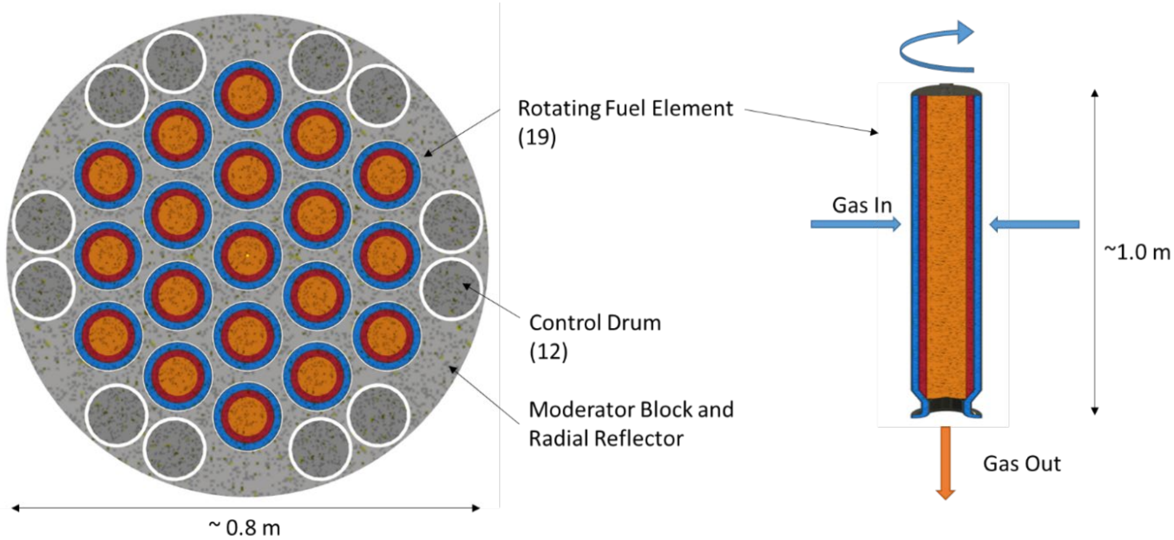

Figure 1. Centrifugal Nuclear Thermal Rocket (CNTR) with 19 Centrifugal Fuel Elements (CFEs)

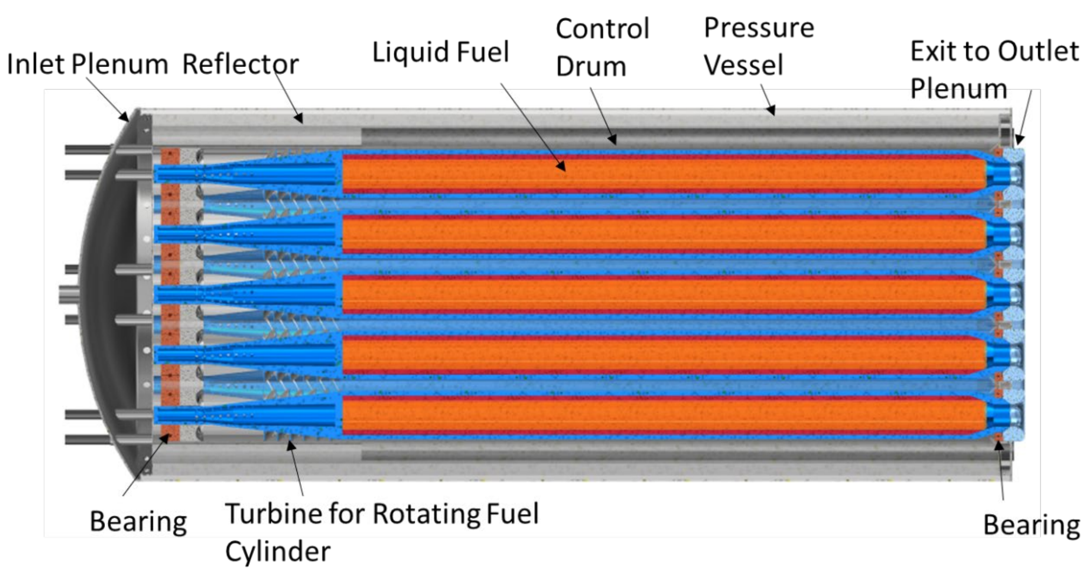

Figure 2. Centrifugal Nuclear Thermal Rocket (CNTR) with Additional Components

By necessity propellant must flow radially inward into the CFE, but that in turn eliminates the need for a thermal insulator between the CFE and the moderator block because the CFE hydrogen inlet plenum is in direct contact with the outer surface of the moderator block. Additionally, during operation there is no thermal stress in the fuel (liquid) and the CFE can be designed to accommodate any fuel / propellant chemical reactions that may occur, reducing compatibility concerns. Other differences compared to solid fuel systems may also be advantageous, such as the removal of fission products from the reactor during operation which may reduce decay heat removal requirements and crew dose from residual in-core radioactivity following shutdown.

In the future, liquid fuel NTP engines may develop to the point that any mix of volatiles could be used as propellant. In that scenario, propellant would essentially be available throughout the solar system with no significant processing required beyond extraction.

The primary challenges of the CNTR are all associated with the CFEs. These include heat transfer and fluid flow within the cylinders; drive mechanisms required for startup, steady state operation, and shutdown; uranium retention and/or recapture; uranium fuel make up (if needed) during operation; and ensuring adequate compatibility between the uranium bearing fuel, the propellant, and the inner wall of the CFE. The remainder of this paper will focus on experimental and computational research being performed to address two of these challenges.

ROTATING FUEL CYLINDER HEAT TRANSFER AND FLUID FLOW

Within each CFE, heat must be adequately transferred between the molten fissile fuel and the gaseous propellant bubbles. To achieve this, the behavior of the propellant as it passes through the extreme pressure and density gradients in the uranium layer must be better understood. This gradient drastically affects the bubble parameters such as size, shape, and velocity, and important components of the heat transfer. Heat transfer begins with heat generation, which is the result of nuclear fission within the molten uranium fuel within each CFE. Neutronics modeling of the CNTR has been performed using the Monte Carlo code OpenMC on several reference CFE geometries, where all geometries share the basic form illustrated in Figure 3, differing only in overall diameters and annulus thicknesses. For a given geometry, the OpenMC model will calculate several parameters of interest including the power distribution, which is important for thermal modeling. It is observed from Figure 4 that the heat generation is greatest at the outer wall of the uranium annulus and decreases as the distance to the inner wall of the uranium annulus is traversed.

Thermal modeling focused on prediction of the maximum propellant temperatures which can be attained in a CFE for a given CFE inner wall temperature, as well as determination whether adequate heat transfer to the propellant bubbles could be attained. Using a finite-difference approach, the thermal model analyzed a single CFE, including the annular fuel region and the surrounding porous CFE inner wall in the analysis, as well as modeling the convective heat transfer to the propellant inside of the clearance gap around the fuel element. The heat transfer in the uranium fuel was treated as solid conduction. Thermophysical property data for hydrogen, liquid uranium, silicon carbide and zirconium carbide were sourced from the literature and integrated into the current model. It also employed models of supporting phenomena such as: bubble formation, bubble velocity, bubble heat transfer, Taylor-Couette flow in the clearance gap, laminar developing duct flow in the SiC CFE inner wall, and energy generation from nuclear decay[5].

Because this model assumes the fuel annulus is stationary, mixing which would likely result from the high-velocity hydrogen bubbles moving through the liquid uranium was neglected. As a result, these predictions can be viewed as best-case outcomes since incorporating the effect of mixing will lower the core temperature. Observations from this analysis include:

- The non-uniform nuclear energy generation presently predicted for these annular geometries constrains the core temperature. As shown in Figure 5, the temperature increase in the propellant is only on the order of 2500 K, yielding a propellant temperature of only 3500K versus the target of 5000 K, with resultant CNTR performance implications.

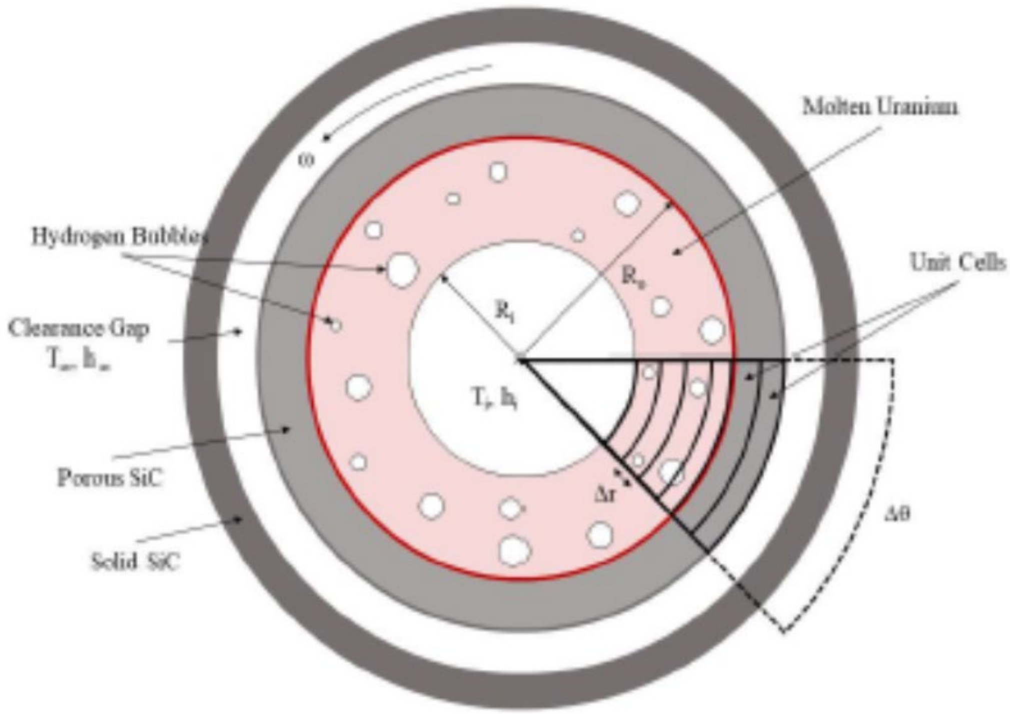

Figure 3. Centrifugal Fuel Element Cross Section[6]

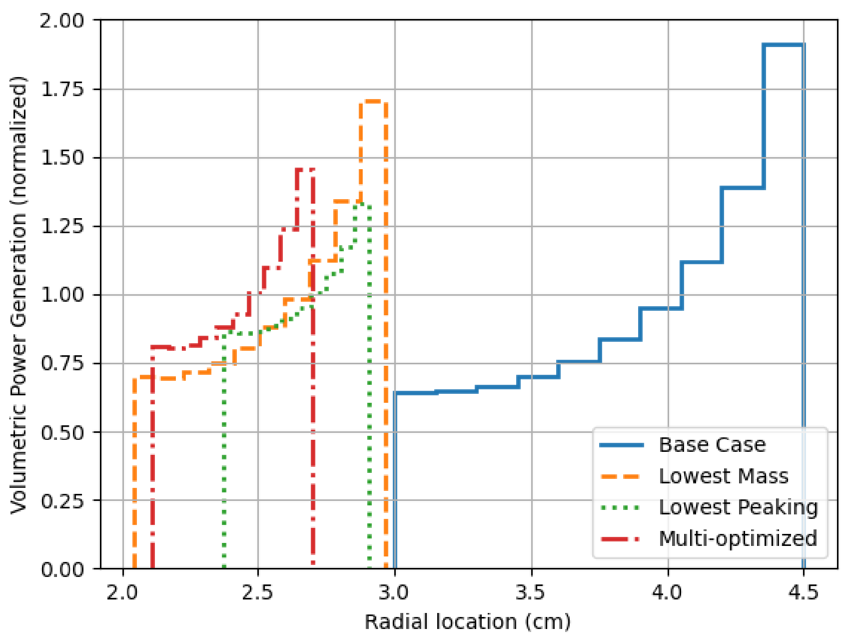

Fig. 4. Radial power profiles for several selected geometry cases. Cases are normalized to an equal average volumetric power, not total power[7]**.**

- The temperature of the propellant bubbles rises to meet the local uranium temperature very quickly, such that by the time the bubbles move approximately 3 mm into the fuel annulus they are at approximately the same temperature as the fuel. This rapid convergence is shown in Figure 5 for one case but is representative of all cases analyzed. Furthermore, the heat transfer profile from the liquid uranium fuel to the gaseous hydrogen propellant was generally invariant to the different geometries analyzed as illustrated in Figure 6.
- High core pressure and high rotational speeds can improve performance. As shown in Figure 8, more efficient heat transfer enabled by a 20 MPa core pressure enabled the propellant core temperature to increase by 3500 K from the CFE inner wall to the bore – in improvement of 40% compared to the reference operating pressure of 5 MPa.

Both the neutronics and heat transfer depend on assumptions regarding the liquid uranium void fraction, which in turn depends on the propellant mass flow rate, the propellant bubble geometry and the velocity at which it transits the liquid uranium annulus from the wall into the bore. Modeling and experimental efforts concerning bubble dynamics. A 3D simulation of buoyancy driven flow is under development to model gaseous hydrogen in the CFEs. The CFEs in an actual spacecraft propulsion system will be dominated by centrifugal forces but also include axial acceleration since the spacecraft accelerates when the propulsion system is running, which poses a challenging set of physics. The goals of the 3D simulations are to (i) assist in projecting anticipated specific impulse and thrust in the CNTR and (ii) validate assumptions regarding void fraction in the liquid uranium fuel. A secondary objective not discussed in this paper is to assist in understanding mass loss from the liquid layer due to splashing or convection and subsequent research on mitigation strategies.

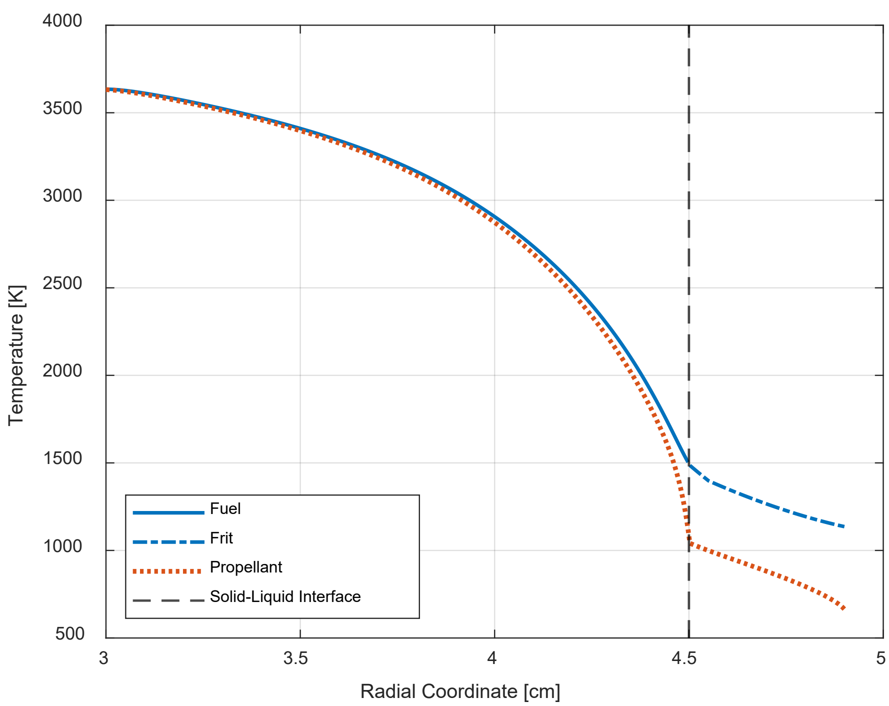

Fig. 5. Temperature distributions for a core diameter of 3.0 cm with a 1.5 cm uranium annulus. The containing wall temperature is maintained at 1500 K and the maximum void fraction is 40%.[5]

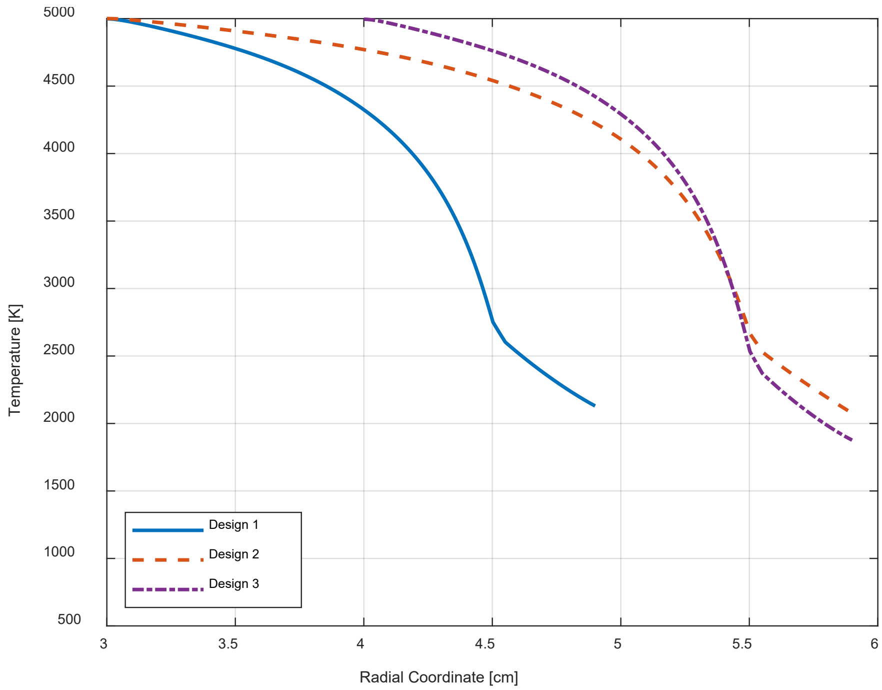

Fig. 6. Fuel and frit temperature profiles for 5000 *K* core temperature for three annulus geometries. Containing wall temperatures are 2500 to 2700 *K* and maximum void fraction is 40%.[5]

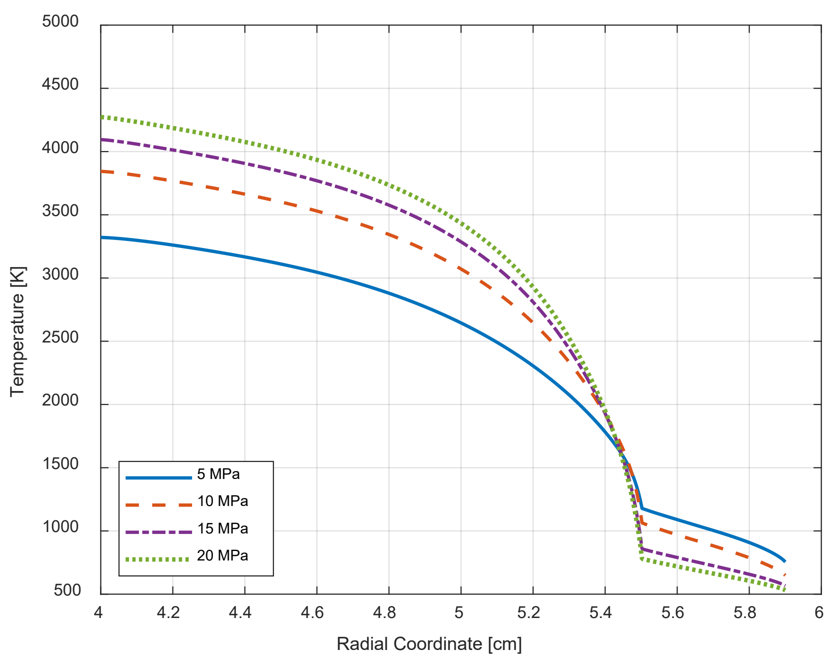

Fig. 7. Propellant Temperatures for a selected annulus geometry with core pressure varied from 5 MPa to 20 MPa. Higher pressure produces higher core temperature for fixed maximum void fraction and containing wall temperature.[5]

A smooth particle hydrodynamic model SPFMax was used to develop the 3D simulations. The most challenging element of this model is an appropriate equation of state for capturing the pressure of the liquid. A modified version of the Tait equation (Eq.1) was used for this purpose, where the pressure scales with P_0, which is a baseline pressure that scales the fluctuations in pressure driven by changes in density.

$$P = P_0 \, tanh\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] + P_a \qquad (1)$$

Where P_a is accounts for small changes in density around ρ_0 but otherwise asymptotically approaches the local pressure P_0 for arbitrarily high densities. This term was added to the Tait equation after numerical simulations revealed that the ρ/ρ_0 term caused nonphysical spikes when liquid particles occasionally were compressed too far beyond the baseline density.[8] Bubble size was modeled using an experimentally derived equation developed by Schrage and Perkins (Eq.2).[9]

$$r_b = \sqrt[3]{\frac{3\sigma D_0}{4g(\rho_l - \rho_g)}} \qquad (2)$$

where D_O is the orifice diameter, σ is the liquid surface tension, g is the gravitational or acceleration value, and ρ_l and ρ_g are the liquid and gas densities respectively. Bubble geometry can be determined by the Eötvös number and Reynolds number, where different regimes for bubble shape result from factors including density, flow speed, viscosity, surface tension, and gravitational forces.[10]

A static testing apparatus was developed to validate the 3D model. The apparatus was adapted from one used in an investigation of bubbly flows in the liquid metal galinstan (a GaInSn eutectic) to calibrate Computational Fluid Dynamics (CFD) models of gaseous flow in liquid metals in the metallurgical industry.[11] Experiments were conducted using two combinations of liquid and gas – water/nitrogen and galinstan/nitrogen. While video could capture the results of the water/nitrogen experiments, X-ray imaging was used to observe the bubble-induced voids in the liquid galinstan in order to estimate their size and frequency, as well as to find the void fraction for correlation to the 3D model predictions. The static apparatus is depicted in Figure 8.

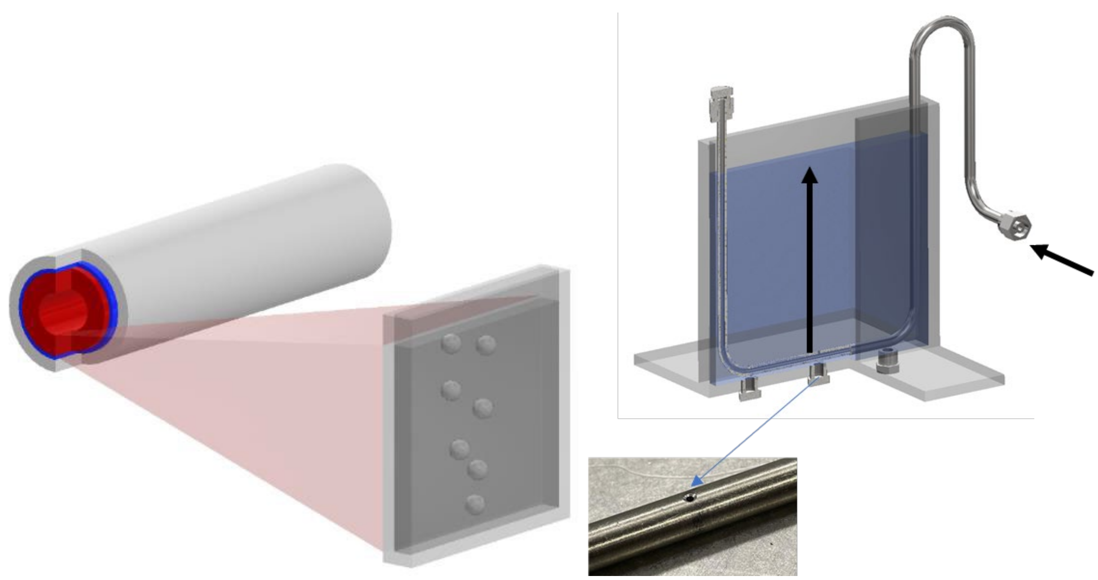

Fig. 8. "Ant farm" container projected as a quasi 1-D section of a CFE (white: CFE porous wall, blue: zirconium carbide wall coating in contact with uranium, red: uranium annulus)[12]

This model was found to work well in static 1G simulations.[13] Over 40 data sets were collected using the static apparatus experiment using the different liquid/gas combinations and different orifice sizes for injecting the gas into the liquid. The data were filtered, and the average bubble shape, size, and velocity were tabulated for the different configurations. Comparing the experimental data to the simulation predictions, the estimated equivalent radius tended to skew lower for the smaller orifice and higher for the larger orifice with the average error ~9%. For the velocity the equation consistently under-predicted (14.3 in./sec) with a few outliers in the experimental data and with an error ~10% as illustrated in Figure 9. It was predicted and observed that the bubbles rapidly achieve terminal velocity and maintain that velocity is essentially constant as it traverses the liquid. Experimental results confirmed initial predictions for spherical cap bubbles, the ideal bubble shape heat transfer. Gas bubbles taking the form of spherical caps offer the highest surface area to volume ratio of the different regimes for bubble shape, providing the best case for heat transfer between them and the liquid they are flowing through. These experimental results indicate that initial conditions during bubble formation only drive bubble mass and formation rate and that CFE environmental conditions will determine bubble size, shape, and velocity.

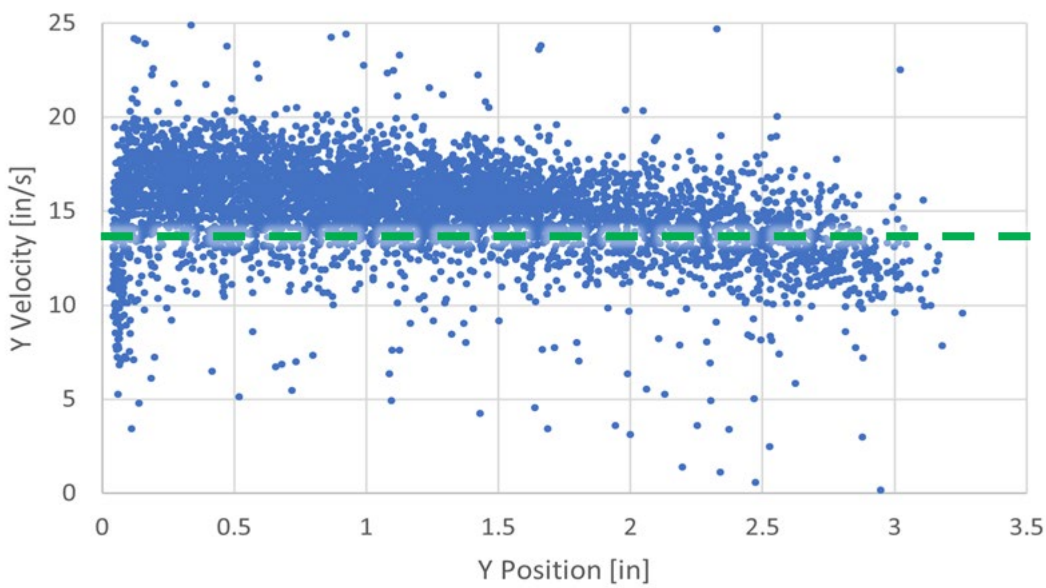

Figure 9. Bubble Velocity for 20 psi Water/Nitrogen Case using a 0.04 inch diameter orifice.[13]

However, the scaling of pressure in a generalized way necessary for predictions of CFEs under various axial accelerations poses additional challenges where the actual localized pressure cannot be anticipated for all the relevant interactions and physical processes which may occur. The literature was surveyed to identify a more robust way of calculating pressure for incompressible liquids to include gravitational, viscous, gas/liquid, and liquid/solid physical effects. Such a technique has been developed for particle-based methods called incompressible smooth particle hydrodynamic (ISPH). ISPH uses a technique based on the Poisson Pressure model, which combines conservation of mass and momentum into an algorithm which solves for the pressure field. It is called 'Poisson' because it involves the solution of a Laplacian in pressure as a function of source terms and various boundaries. This technique is particularly useful in this application since the pressure field emerges without requiring a precise calculation of density, which is highly error prone in complicated 3D problems such as those of relevance to CNTR models. This technique and implementation will be described in a future work.[7]

Additionally, while the foregoing 3D model worked for a static condition, a more general solution to the prediction of bubble velocity is needed for the dynamic environment associated with a rotating CFE. The equations of motion for the bubble can then be used to predict its path and behavior through annulus of Uranium within the CFE accounting for drag, buoyancy, and Coriolis effects. The terms for the bubble equations of motion are constants or derived from Eq. (2) except for the drag coefficient which is more difficult to define for the bubble. A survey of the literature revealed a general equation to describe the fluctuating drag coefficient for a bubble as described in using the Reynolds (Re), Eötvös (Eo), Weber (We), and Morton (Mo) numbers, which in turn arederived from the velocity and fluid properties.[14] This technique and implementation will also be described in a future work.

Once developed, the general 3D model will also be experimentally validated. The Bubbling Liquid Experiment Navigating Driven Extreme Rotation (BLENDER) apparatus is currently under development at UAH is graphically depicted in Figure 10. The BLENDER consists of a solid stainless-steel construction with two configurations – (i) a sapphire glass and steel front face for optical observation as shown in Figure 10 and (ii) a cut carbon fiber radiolucent face for x-ray radiography. The apparatus was designed in a way to have interchangeable injector faces allowing for different patterns, sizes, and materials to be studied. The BLENDER is designed to operate at speeds up to 7000 RPM, which is the upper range proposed for a CFE. It is also designed to accommodate and chamber pressures from 500 psi or 3.5 MPa up to 3000 psi or 20 MPa, which bounds the proposed operating condition for a CFE. The apparatus in development, which has completed a critical design review and is presently in fabrication as of this writing. Checkout operation of the BLENDER is planned for completion in the spring 2023 semester. Once successfully checked out, experimental runs will commence with water/nitrogen and galinstan/nitrogen for a range of experimental conditions including annulus thicknesses, operating pressures, rotational velocities, mass flow rates, and CFE inner wall porosities, allowing validation the dynamic 3D model and subsequent research into optimization of relevant CFE design parameters.

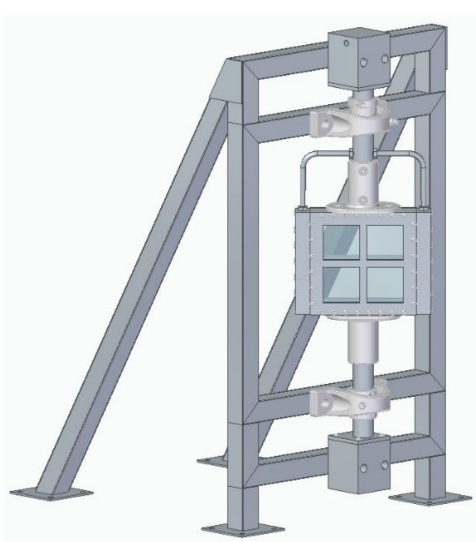

Fig. 10. BLENDER Apparatus

DRIVE MECHANISMS REQUIRED FOR STARTUP STEADY STATE OPERATION AND SHUTDOWN

The initial state of the nuclear fuel tubes before starting the engine is expected to be at space temperatures (~79 K). The uranium metal fuel would be manufactured in tubular form and fitted into the fuel tubes. The uranium fuel heats up as the reactor is started and will reach a melting point of 1408 K under a safe ramp-up rate of reactor power. It is necessary to start rotating the fuel tubes before the uranium goes through a solid-to-liquid phase change. When the uranium fuel is in solid metallic form, it is not possible for hydrogen to flow (bubble) through the fuel to reach the center exhaust region of the annular fuel. Therefore, an alternative method of rotating the tubes is needed during the solid phase conditions.

The axial temperature profile in the uranium fuel will be directly proportional to the neutron flux because the fission rate is determined from the neutron flux and the macroscopic fission cross-section. The axial neutron flux will have a cosine-shape profile peaking at the midpoint of the core region. The core radial flux profile will have a Bessel function profile peaking at the centerline of the reactor core, so the fuel tubes closest to the center of the core will have the highest fission rates and temperatures. Therefore, the melting of the solid uranium into the liquid phase will occur first toward the center of the reactor core. Melting will start at the midpoint and propagate to the end-points of the tubular uranium region.

During the 2021-2022 academic year, two undergraduate student design teams (five members on one team and four on a second team) at the University of Rhode Island worked on various design concepts for fuel-tube rotation from cold starting conditions to full operational conditions. One team focused on the method of rotation during the cold start phase to the melting point of uranium fuel.[15] During this phase, propellant flow through the uranium layer is not possible because of the solid state of the fuel. Also, full rotational speeds are not needed during the startup.

The 2021-2022 teams combined their efforts in designing a hybrid method of rotation using an electric motor for low speeds during the startup (pre-melt) phase and a gas turbine for high-speed operating conditions for the liquid phase post-melt startup into steady-state operation.[16] Figure 11 shows the initial build of a prototype apparatus. The electrical motor will disengage through a clutch device at a set-designed rotational speed. At that point, the gas turbine will drive the fuel tube. With the improved prototype device, several variations of the gas turbine design could be tested. Figure 12 shows the scaled-down fuel tube with the turbine section.

During 2022-2023 academic year, two teams of five students each have been assigned to design and build an experimental device for phase change experiment under rotation and design an optimal turbine for a maximum range of operational speeds. The work of both teams is currently in progress. The first team is designing an experimental device to rotate a working fluid under phase change. The first version of the experiment will focus on water as the working fluid. Initially, liquid water colored with a transparent dye will be used to demonstrate the fluid mechanics of rotation. Next, a tubular ice form will be used to demonstrate phase change under rotation and centrifugal force. Finally, a low-temperature casting alloy (Bismuth, Cadmium, Lead and Tin) with a melting temperature of 158ºF will be utilized. This alloy can be melted with hot air or induction. Figure 13 shows the experimental device as currently designed:

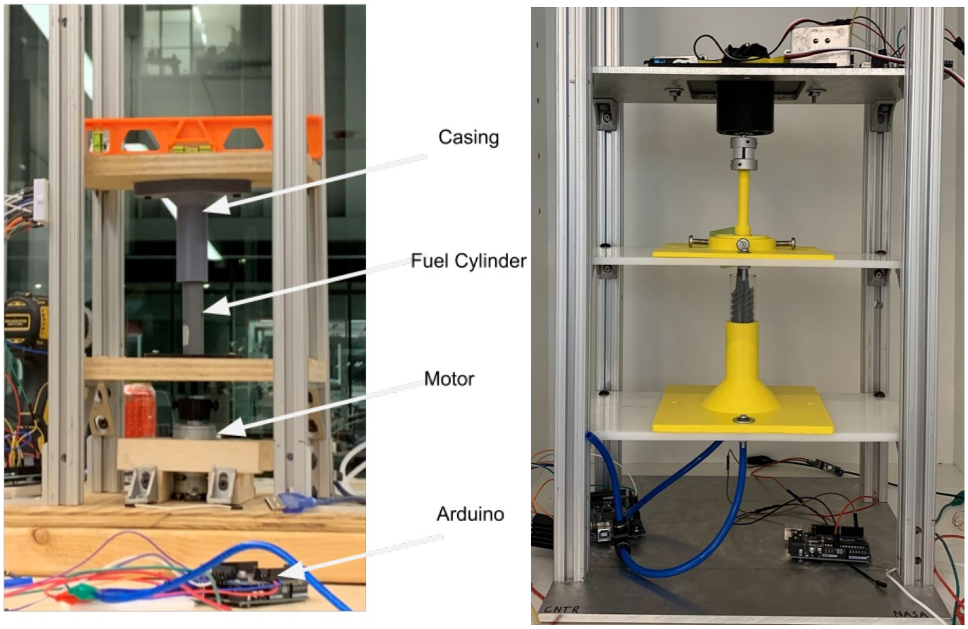

Figure 11. Fuel Tube Drive Initial Prototype and Improvement (right).

Figure 12. CAD model of the fuel-tube with the turbine section.

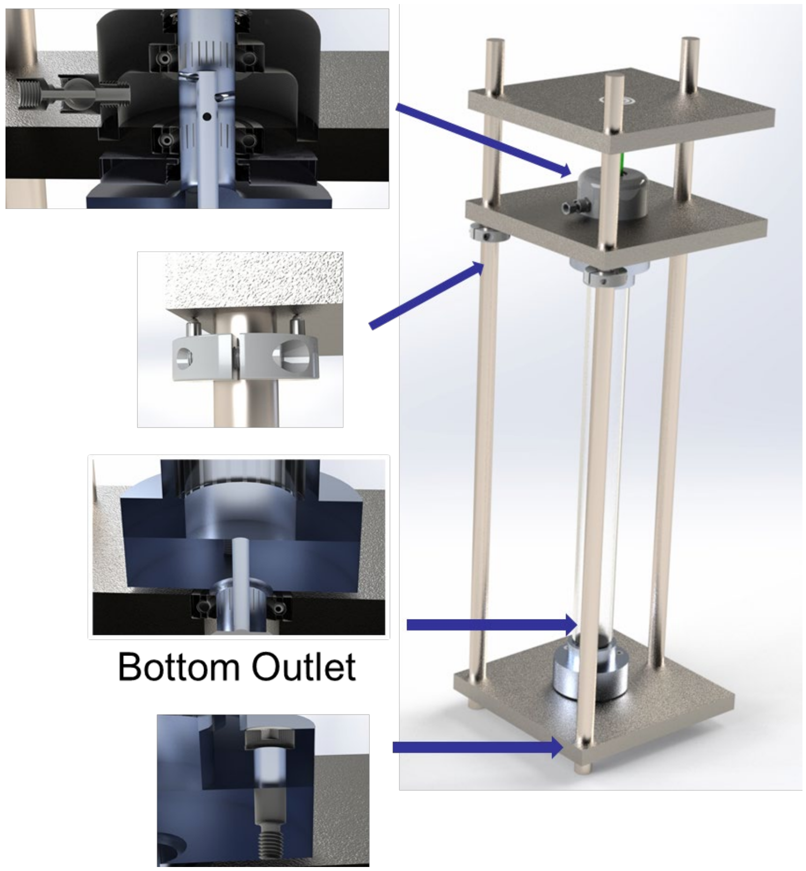

Figure 13. Experimental device for phase change under rotation.

The second group is working on the optimal design of a gas turbine for the rotating tubes using CFD. Many different turbine blade shapes and arrangements have been investigated. Figure 14 shows a linear/nonlinear blade configuration and the calculated streamlines and gas velocities. An experimental device has also been designed to conduct experimental measurements to compare to the CFD calculations. This work will be completed in May 2023.

CONCLUSION

Space nuclear propulsion systems could be instrumental in enabling extensive exploration and development of the solar system. Much of the technology being developed for solid fuel NTP engines will be directly applicable to higher performing liquid fueled engines. A primary difference between the engines will be that the reactor powering the liquid fueled engine will use rotating fuel cylinders containing molten uranium metal or uranium carbide instead of the stationary fuel elements used in traditional solid fuel NTP designs.

University research has begun to address challenges associated with the rotating fuel cylinders. Although current research is still at a very early stage, no fundamental "showstoppers" with the CNTR approach have been identified. At a more general level, the development of any high thrust propulsion system capable of heating propellant to 5000 K could have numerous potential applications, including greatly enhanced maneuverability in cislunar space, fast round-trip human Mars missions, deep space missions, and direct utilization (as propellant) of volatiles found throughout the solar system. The high density of the liquid uranium or uranium carbide fuel reduces the minimum critical size of the reactor, providing additional potential mission benefits.

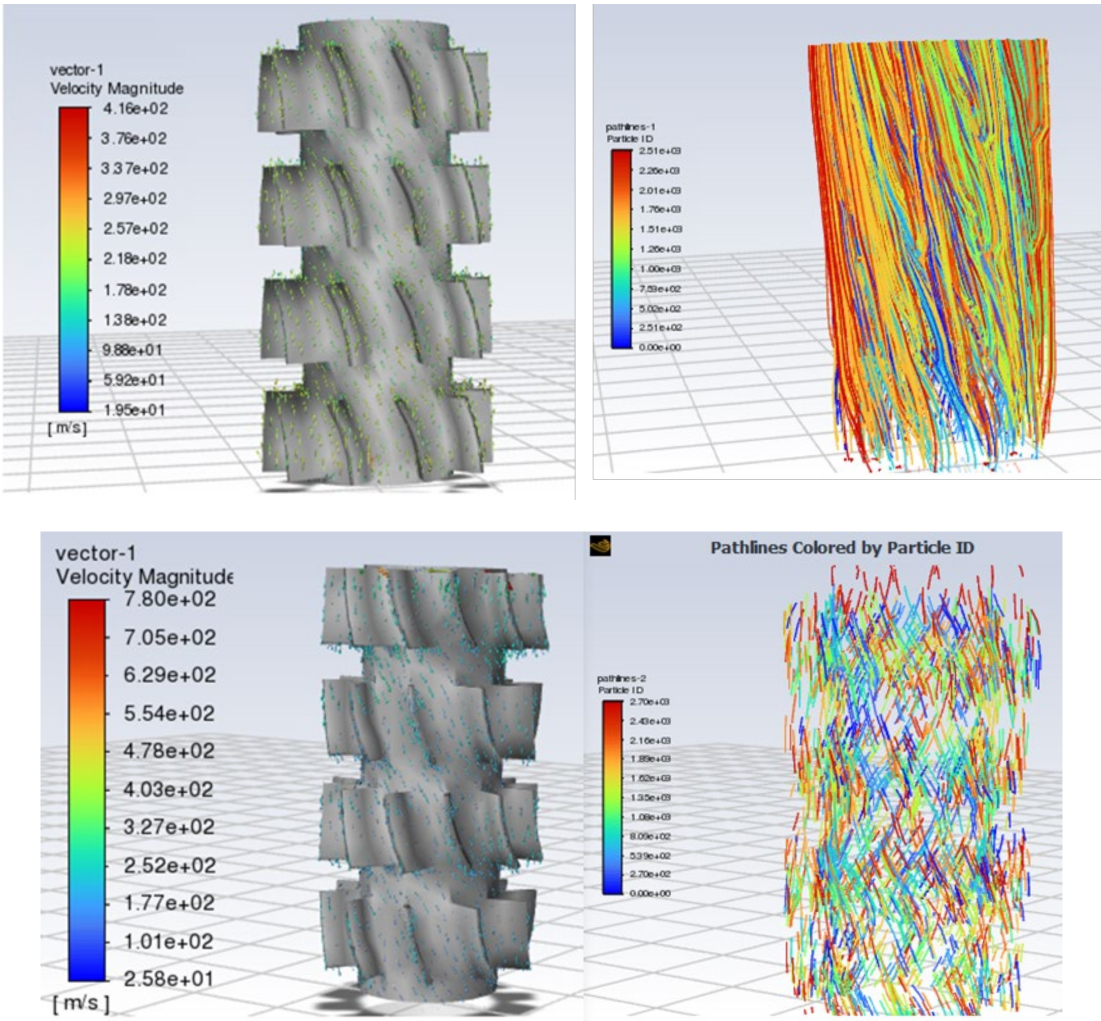

Figure 14. CFD studies of turbine design variations (top linear, bottom nonlinear).

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