Multiphysics Modeling of a Single Channel in a Nuclear Thermal Propulsion Grooved Ring Fuel Element

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Abstract. In the past, fuel rods have been used in nuclear propulsion applications. A new fuel element concept that reduces weight and increases efficiency uses a stack of grooved discs. Each fuel element is a flat disc with a hole on the interior and grooves across the top. Many grooved ring fuel elements for use in nuclear thermal propulsion systems have been modeled, and a single flow channel for each design has been analyzed. For increased efficiency, a fuel element with a higher surface-area-to-volume ratio is ideal. When grooves are shallower, i.e., they have a lower surface area, the results show that the exit temperature is higher. By coupling the physics of turbulence with those of heat transfer, the effects on the cooler gas flowing through the grooves of the thermally excited solid can be predicted. Parametric studies were done to show how a pressure drop across the axial length of the channels will affect the exit temperatures of the gas. Geometric optimization was done to show the behaviors that result from the manipulation of various parameters. Temperature profiles of the solid and gas showed that more structural optimization is needed to produce the desired results.

Keywords: Nuclear Thermal Propulsion, Fuel Element, Heat Transfer, Computational Fluid Dynamics, Coupled Physics Computations, Finite Element Analysis

EXISTING NUCLEAR THERMAL FUEL TECHNOLOGIES

Missions to Mars will benefit from propulsion systems with performance levels exceeding that of today's best chemical engines. Nuclear Thermal Rocket (NTR) technology has the greatest potential for the near-term success of increasing performance, reducing cost, and increasing safety margins by reducing total fuel required, thus reducing total launches for Mars missions. During the 1960's and 1970's, the United States embarked on a nuclear rocket program called Rover/NERVA, which was successful in developing high performance nuclear fuel forms. Solid core NTR engines during the Rover/NERVA program demonstrated specific impulses around 850 seconds, which are significantly greater than those possible with maximally efficient chemical engine systems with around 450 seconds. In spite of this success, however, there surfaced a number of materials and configuration issues which limited the ultimate performance of these engines. In particular, the relatively heavy and difficult to fabricate prismatic fuel block, with its small surface-to-volume ratio (≈ 5.6 cm^{-1}), caused large core pressure drops which consequently limited the engine thrust- to-weight ratios to around 3 or 4. Additionally, corrosion occurred in the long flow channels of the fuel rods.[1]

To address the problem of low thrust-to-weight ratios in the Rover/NERVA engine design, a new configuration was proposed. This configuration, called the particle bed reactor, used fuel that had a much higher surface-to-volume ratio (≈ 40 cm^{-1}) and a lower pressure drop. This engine was projected to have a thrust to weight ratio of 20 or greater, although the design ultimately proved unsatisfactory because of inherent problems with thermal instabilities resulting from unconstrained propellant flow through the fuel particles.[2]

An innovative, new fuel element called the Grooved Ring Fuel Element (GRFE) could enable the development of a new NTR system with specific impulse of around 1000 seconds or higher using new carbide fuel materials manufactured with newly available ceramic manufacturing technologies. Increase in specific impulse from 450 seconds to 1000 seconds will reduce propellant required in orbit to save 4 Space Launch System (SLS) launches for a Mars mission. The GRFE, with its high surface-area-to-volume ratio, has the potential to provide higher power densities, yielding NTR engines with a higher thrust-to-weight ratio around 10 to 15. This is much greater than the NERVA engine design, which used hexagonal axial flow reactor fuel elements.

GROOVED RING REACTOR CONCEPT

The GFRE is a concept that combines the best features of the Rover/NERVA fuel element and the particle bed fuel element and eliminates many problems with pressure drops, corrosion, thermal instabilities, and intricacies in fabrication methods. On the surface, the GFRE has a propellant flow configuration which is roughly similar to that envisioned for the particle bed fuel element; however, there are significant differences. A conceptual drawing of the fuel element is shown in Figure 1. As illustrated, cold hydrogen enters reactor and is diverted down along the outside edge of the grooved fuel ring stack. The hydrogen propellant enters the stack of rings and flows radially along the grooved faces of the individual fuel rings. The rings are held in place by a hexagonal structure which directs the hydrogen flow into the fuel ring stack. The hexagonal structure may or may not contain moderating material depending upon whether the reactor is designed to be a fast reactor or thermal reactor. Because cold hydrogen flows in the region between the outer edge of the rings and the inner region of the hexagonal support structure, the support structure remains fairly cool during operation and only the rings experience high temperatures.

Figure 1 illustrates an example of an individual grooved fuel ring where the flow area remains constant along the face of the ring from its outside edge to its inside edge. Other groove patterns on the fuel ring faces could be designed to achieve variable cross-sectional flow areas which would be more optimal from a fluid dynamics standpoint. As the hydrogen flows along the face of the fuel ring, it picks up heat until it finally exits into the interior of the fuel ring. The hot hydrogen then flows axially down the center of the fuel ring stack until it finally exits the fuel element assembly at the bottom. Preliminary calculations indicate that the fuel surface-to-volume ratio for the fuel rings should approach that of the particle bed fuel. It should also be possible for a moderated fuel element to yield very favorable radial power profiles where the power density decreases exponentially radially inward toward the center channel. Such power density profiles minimize thermal gradients within the fuel ring, while allowing the entire ring to operate near its maximum allowable temperature.
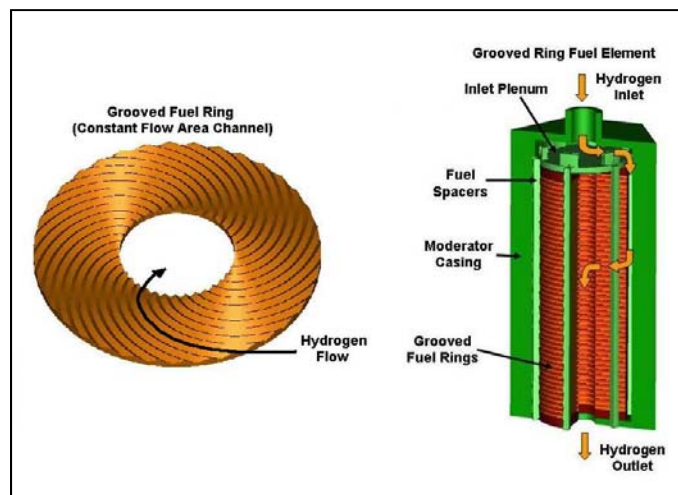

Figure I. The grooved ring fuel element (left) is a grooved disc, through which heated gas flows. Discs are placed in a reactor (right), to create a stack efficient for nuclear thermal propulsion applications. Gas enters the top, flows through the grooves, then flows out the bottom.

Because the grooved structure of the fuel rings does not require inaccessible passages for the propellant flow, difficult extrusions or machining techniques used for NERVA type fuel elements will not be required. This ease of fabrication will allow fuel elements to be made of fairly exotic materials such as uranium tricarbide that present difficulties under normal circumstances due to extreme hardness and brittleness material properties.

In an effort to design a more efficient fuel element that has a higher surface-area-to-volume ratio and higher specific impulse, the fuel element was modeled, analyzed, and geometrically optimized to show an improvement over the earlier designs. Several different models were made, each with varying angle spacing for straight and curved channels.

Baseline Designs and Models

Several examples of the GRFE (grooved ring fuel element) have been designed to maximize the surface-area-to-volume ratio of reactive surfaces in nuclear propulsion fuel elements. For comparison, the NERVA design was used to show significant improvements in the ratios of reactive area to volume using a verified wxMaxima code. Most baseline designs yielded surface area improvements of at least 100% over the surface area values for a hexagonal fuel element with the same volume. As more grooves were added, surface area increased significantly. Several designs were created so that different geometries could be considered. Many discs with both curved and straight grooves were modeled.
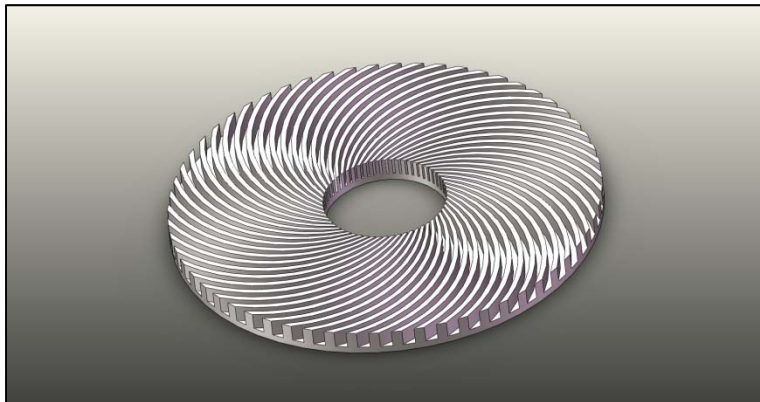
Figure II: After finding acceptable geometries, straight grooves in Cartesian coordinates can be converted to radial coordinates, forming a disc with curved grooves. It is possible for flow channels and grooves to have constant and equal widths.

The baseline design had an outer radius of 20.0mm, an inner radius of 6.3mm and a thickness of 1.0mm. This baseline was modified throughout optimization efforts. To simplify initial finite element computations, the straight groove design was used for initial analysis.

TECHNICAL APPROACH

A heat transfer analysis was done for several models in an attempt to obtain the temperatures of the hydrogen and the fuel element. Lower temperature changes should result in a reduction of thermal stress, improving the structural integrity of the fuel element; therefore, the goal was to create a structure with geometry such that the heat flux differentials are minimized. Rather than modeling the flow through an entire disc, a small portion of each disc was analyzed. Heat transfer physics coupled with those of turbulent flow will show how the element cools during use.

Single Channel Modeling

Initially, discs with straight and constant-area flow channels were analyzed. When temperature, velocity and pressure profiles are acceptable, the straight grooves can then be converted to curved grooves. Any straight-grooved

design can be converted to a curved-grooved design by using equation 1, which should be done at a later date. This equation uses inner and outer radius values to find the angle value at with the groove terminates on the disc interior.

$$\theta = \frac{\sqrt{r_o^2 - r_i^2}}{r_i} - \cos^{-1}\frac{r_i}{r_o} \qquad (I)$$

For simplification, initial multiphysics models were performed only on one channel and one groove. This approach was further simplified by reducing the structure being analyzed to ½ of one channel and ½ of one groove. Additionally, only ½ of the disc base, which is the lower portion without grooves, was analyzed. Since the discs were assumed to be stacked, the flows through any disc were assumed to be affected by the transfer of heat from the disc stacked directly above. The area of interest in Figure 3 shows an example of a disc portion to be analyzed, resembling the model shown in Figure 4.
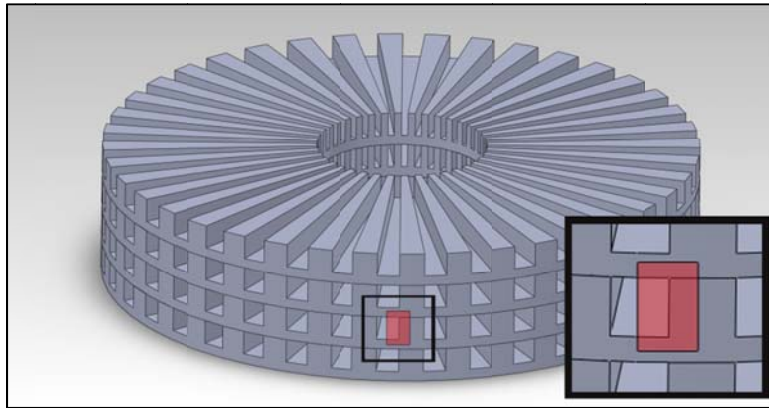
Figure III. Four discs are shown in part of a stack. The solid portion, shown in red, represents an example of ½ of the disc base being modeled, and ½ of the disc base that would be stacked above it. Additionally, only ½ of the flow channel and solid groove were analyzed. Symmetrical boundary conditions are used on domains that are halved.
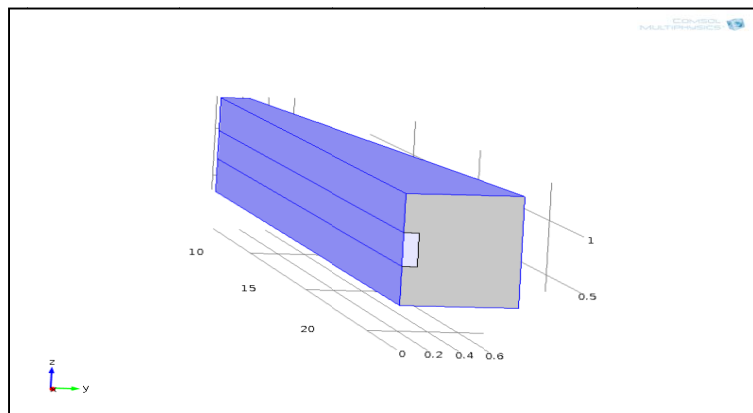
Figure IV: Illustrated is an example of ½ of a single channel with ½ of a groove. The highlighted portions indicated boundary conditions that were designated as symmetrical.

Model Inputs and Boundary Conditions

Properties for hydrogen gas and uranium zirconium carbide, found in previous research, were used for these computations.[3] Initial conditions were specified as 0 for all components of the velocity field and a temperature of 293.15 K. A general heat source was applied at a constant 10×10^{10} W/m³. Power density was varied occasionally during studies to observe the differences in behavior of the temperature profiles. Because power density was not expected to be exactly constant across the entire geometry, all final designs should undergo analysis using a

neutronics code to show power variations to replace the constant power density definition initially used for the models.

The hydrogen inlet had a given pressure of 6.89×10^6Pa, and no viscous stress. For heat transfer purposes, the temperature specified for this boundary was 293.15K. A general heat transfer outflow was given for the hydrogen exit. The reference velocity scale was 1m/s, turbulent intensity was 0.05, and the turbulence length scale was 0.01m. The hydrogen exit pressure was usually specified at around 6.83×10^6Pa, but was varied during parametric studies.

Many symmetrical boundaries were applied due to the halving of geometries, as illustrated in Figure 4. Symmetrical geometries and volumes exist normal to these boundaries. It should be noted that any time a geometrical feature was halved, boundary conditions on these features will be assumed symmetrical, which speeds computations.

RESULTS OF HEAT TRANSFER AND TURBULENT FLOW COMPUTATIONS

Parametric Studies

Parametric studies were performed to reveal the effects of pressure drops on the temperatures of the gas and solid. Ranges for which the studies were done are shown in Figure 5 in given increments. Each model had a different pressure range with which it could complete computation. The figure below shows how large pressure differences resulted in higher velocities through the solid, causing the gas to be cooler as it exited. When the pressure drop was lower, the gas moved slower through the channels, increasing the temperature as it moved towards the exit. In order to maintain a significant exit velocity, a larger pressure drop was required. This was done by adding thinner channels and decreasing the separation angle, which also increases the number of channels.
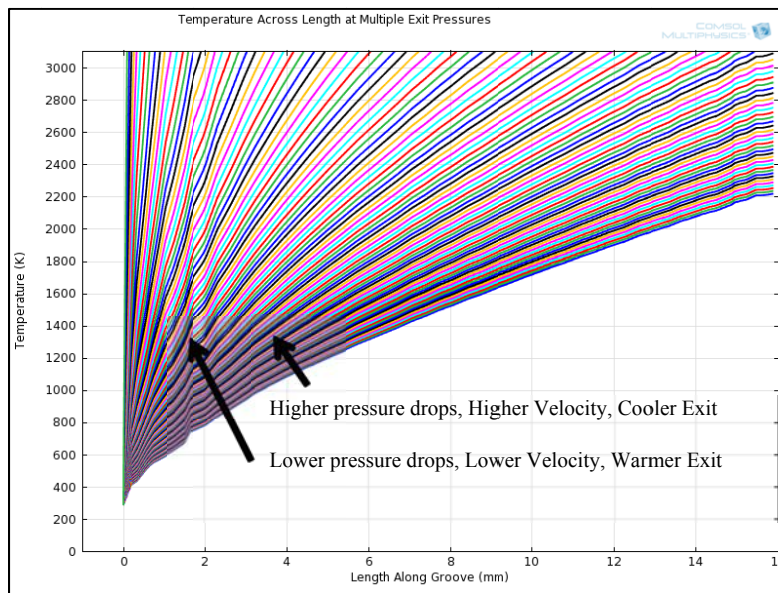
Figure V. Exit temperatures were found to be lower with larger pressure drops. This graph shows the effect of small pressure variations that were within around 10.0Pa of the inlet pressure, which is a result of a large flow channel. This low pressure drop is associated with a low exit velocity. When the flow channel width was decreased, pressure drop varied in increments of around 6.9×10^4Pa (10psi), which was assumed to be ideal for the desired exit velocity.

Heat Transfer Results

Heat transfer analyses were done on the solid and gas domains of the model. Results were plotted in 3D, and 2D plots were made for temperature changes along the length. Flow channels of the initial design were shortened to accommodate a higher exit velocity. As a result, the surface-area-to-volume ratio suffered, and temperature of the solid became too high with the smaller gas domains. It was found that adding more flow channels decreased temperatures in the solid. Figure 6 compares the steady-state solid temperatures of a disc with 5° separation angles, to one with 1° of separation between channels. More gas was available to take away more heat with more flow channels. Temperatures were also controlled with deeper flow channels and elongation of the channels by a larger outer radius.
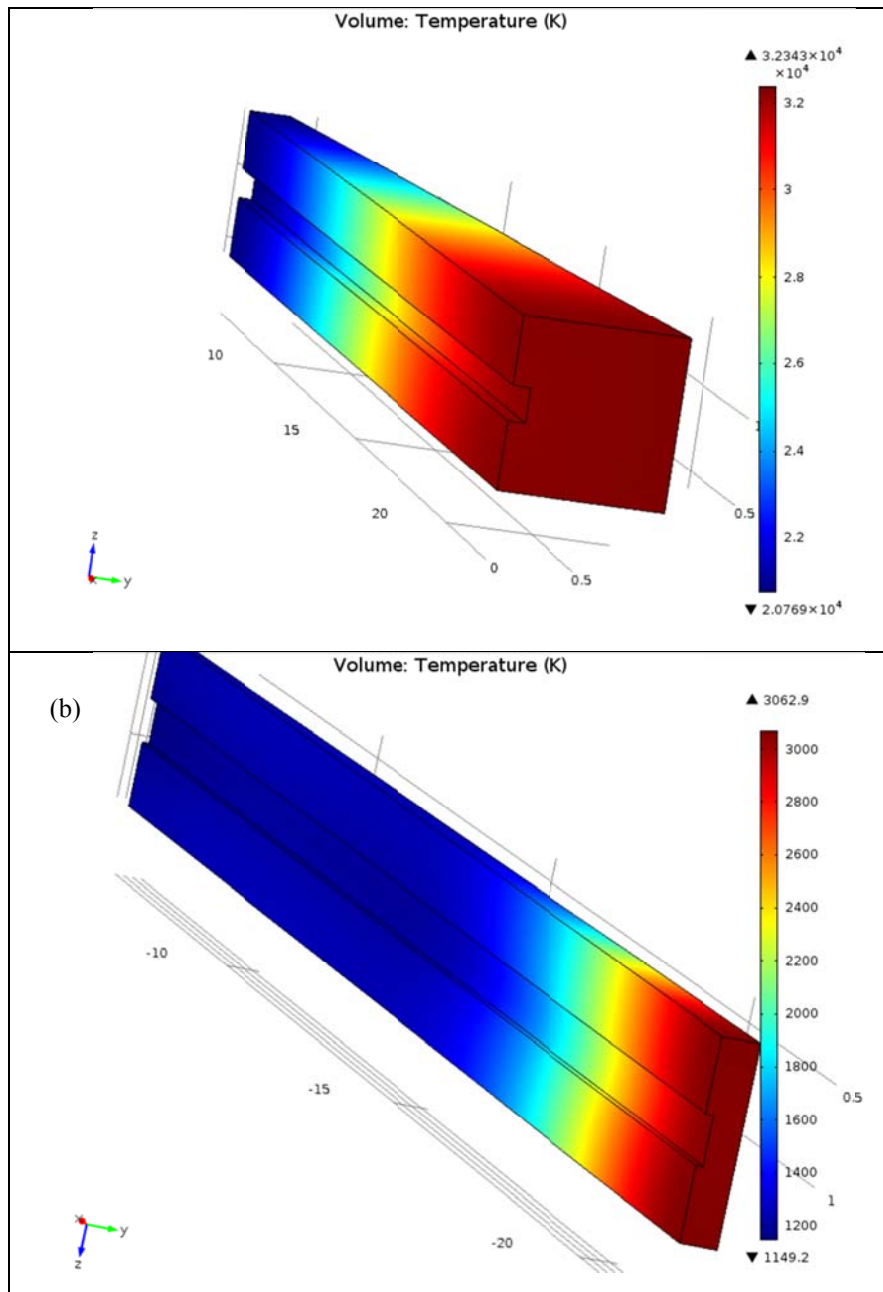
Figure VI: (a) High temperatures are expected with larger flow channel angles of separation. (b) With deeper, elongated flow channels and smaller angles of separation, the fissile material cools. The outer radius was increased by 2.0mm.

To prove the effectiveness of cooling the solid with more flow channels, five models were analyzed and compared. Figure 6a shows a disc with 5° of separation and 72 flow channels. Models with 2° and 1° seperation angles were found to yeild lower temperatures. Temperatures for the solid decreased quickly as the gas temperature decreased slowly. While other geometries remained the same for the first 3 models, the flow channel widths had to be decreased in order to accommodate the extra grooves. Model 4 had a deeper flow channel, which yeilded lower temperatures for both the solid and gas. All models except for model 5 had the same inner and outer radius values. To show the effects of longer gas flow channels, Model 5, shown in Figure 6b, was constructed with a larger outer radius. By increasing the outer radius by 2mm and maintaining the deeper groove used in Model 4, the maximum solid temperature at steady-state was around 3062K, and the gas exit temperature was 975K .

(a)

(b)
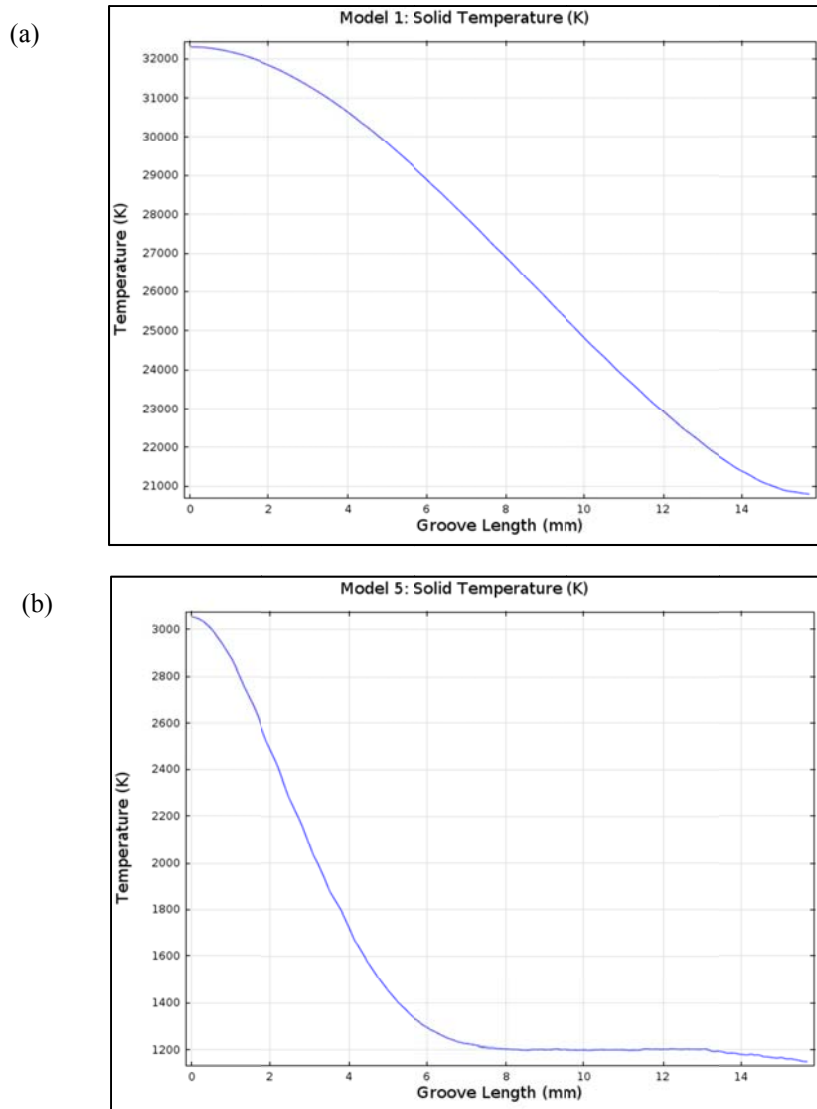
Figure VII: (a) Solid temperatures cool along the length of the grooves slowly when there is a larger volume of solid. (b) When there are more channels the grooves are thinner, so that the solid cools faster.

Figure 7 shows centerline temperatures for the Models 1 and 5. Model 1, found in Figure 7a, cools much slower with a higher solid volume. Figure 7b shows an example of groove temperatures decreasing rapidly at the exterior portions and decreasing more slowly when approaching the disc interior. The exterior-most areas of the disc cooled

much faster as the channels become thinner and longer. This was significant because a more constant temperature is preferred to mitigate the risk of thermal stresses. Ideally, the entire groove should have small temperature changes. Table 1 shows a summary of heat transfer results for all five models.

Table 1: Summary of Heat Transfer Results

Model	Flow Channels	Outer Radius (mm)	Channel Height (mm)	Max Solid Temp (K)	Gas Exit Temp (K)
1	72	20	0.2	32343	2507.00
2	180	20	0.2	9616.5	1642.50
3	360	20	0.2	3224.1	960.10
4	360	20	0.25	2784.9	786.80
5	360	22	0.25	3062.6	975.00

CONCLUSION

Processes for 3D modeling, discretizing, meshing, identifying boundary conditions, and post processing were successfully defined, and models that coupled turbulent flow physics with those of heat transfer have been used to generate profiles for pressure, temperature, velocity, and other important parameters. Results showed expected behaviors of these parameters, which must be considered when designing elements using brittle carbide materials. Failures resulting from thermal stress can be prevented by observing the temperatures found from analysis.

Disc designs will be further detailed by the addition of many more flow channels. Comparisons between the S/V (surface area to volume ratio) of the NERVA fuel and the final GRFE design/designs can be easily implemented. In order to create an automated method of finding an S/V ratio of a hexagonal rod structure with the same volume as the GRFE in consideration, a code was written in wxMaxima. This code has already been verified by using SolidWorks volume and surface area calculations. Future analysis will advance to incorporate the entire fuel element stack. The modeling will look at additional GRFE configurations for a more optimal system.

Neutronics calculations using Monte Carlo N-particle (MCNP) code will be performed on the fuel element designs to determine expected power profiles resulting from fuel and moderator density variations. These power profiles will be incorporated into CFD calculations to optimize existing fuel ring heating profiles.With a design of a working GRFE model, a representative GRFE will be fabricated using various fabrication techniques (cold isostatic press, hot isostatic press, and/or rapid prototyping) to demonstrate producibility. Long-term plans include test article design and test planning in the Nuclear Thermal Rocket Element Environmental Simulator (NTREES), which uses induction heating to simulate the expected high-temperature environment.[4]

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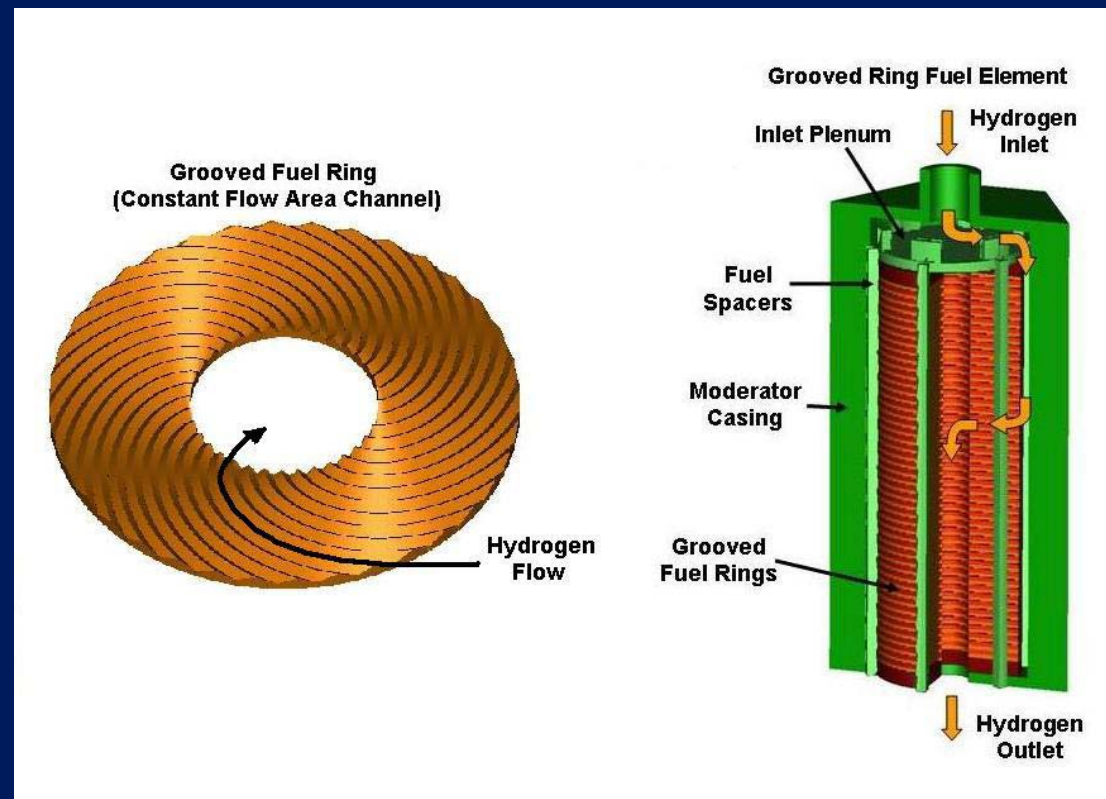
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- Reactor contains many stacks of discs
- Hydrogen flows through the grooves on the discs
- Gas is heated as it travels to internal opening of disc

Grooved Fuel Ring (Constant Flow Area Channel)

Hydrogen Flow

Grooved Ring Fuel Element

Inlet Plenum

Hydrogen Inlet

Fuel Spacers

Moderator Casing

Grooved Fuel Rings

Hydrogen Outlet

Disc Example

- Discs with curved grooves and straight grooves were modeled in 3D
- All disc showed significant improvements of surface area to volume in relation to hexagonal fuel portions of the same volume
- Straight-grooved models were chosen for initial analysis due to modeling simplicity
- It is possible to have a disc with constant flow channel widths and constant groove widths
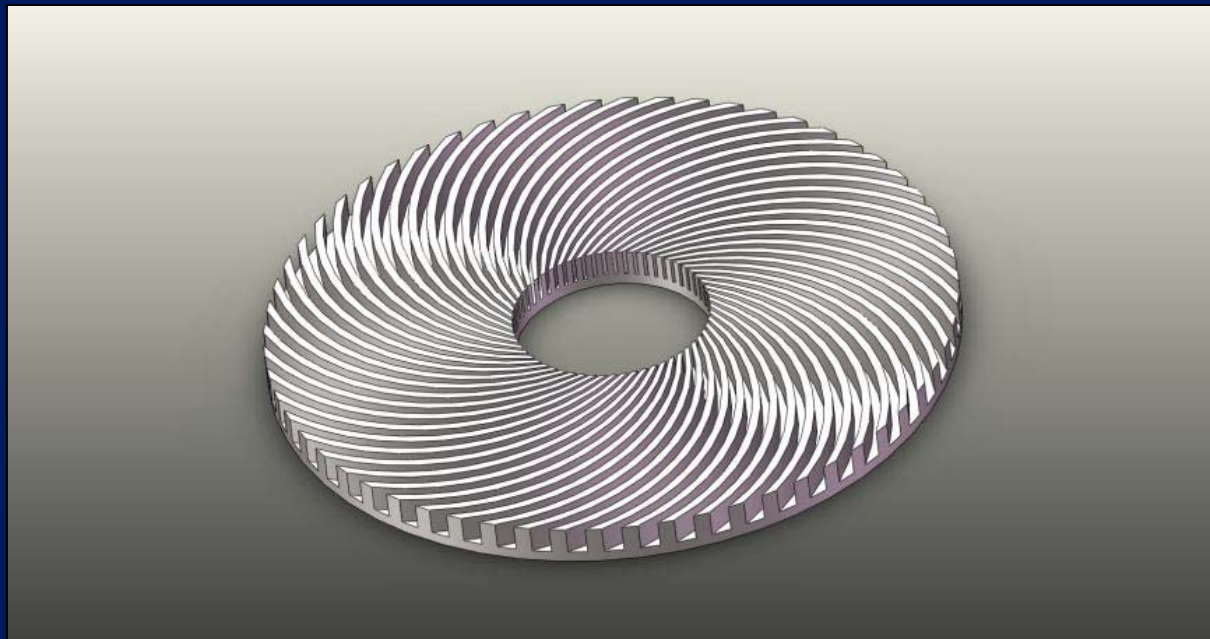
- Models are based off the following: ½ of disc base, ½ of groove, ½ of flow channel, ½ of disc base of disc placed on top
- Future work includes analysis of several grooves, and an entire stack
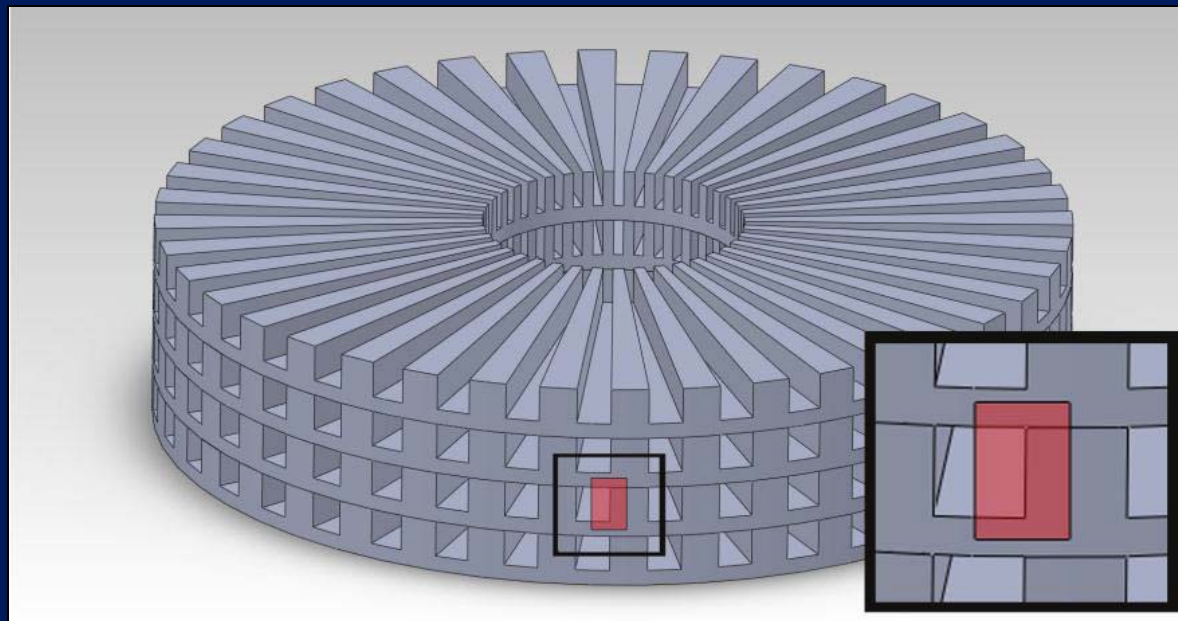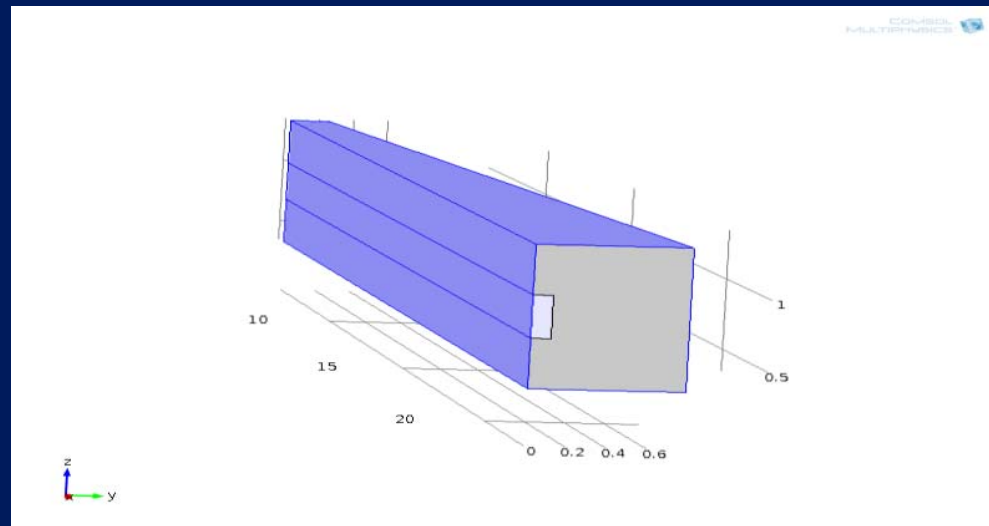
Technical Approach

- Graphic below shows the portion of the discs used for analysis
- Boundary conditions highlighted in purple are assumed symmetrical for heat transfer
- Only one boundary in the flow domain (also in purple) is assumed symmetrical

Inlet pressure: 6.89×106Pa (1000 psi)
Exit pressure: 6.83×106Pa (90 psi)
Constant Power Density: ~10^{10} W/m³

Parametric Studies

- Parametric studies show how pressure increments can change the exit temperature of the gas
- Below, increments of 1/1000 of the pressure unit drastically change the exit temperature, showing that the flow channel was too large
- Parametric studies of pressure revealed that flow channel had to be carefully optimized to yield acceptable temperatures


Temperature Across Length at Multiple Exit Pressures
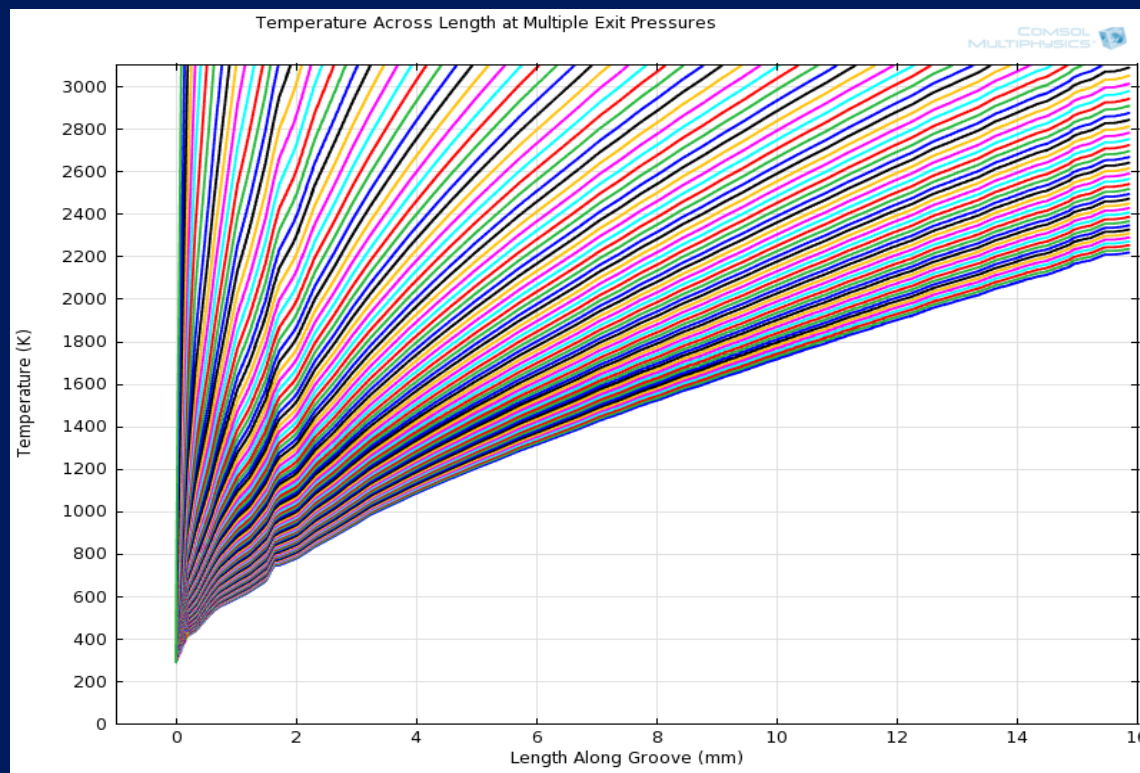
Temperature Results

- Many disc were analyzed to show the difference in solid state conditions
- Initially, a disc with large grooves were used
- After parametric studies showed unacceptable pressure drops along the channels, models with smaller grooves were considered
- Exit temperatures of the gas were found acceptable (~3000) with a pressure drop of around 0.01×10^6 Pa (10 psi), but the surface-area-to-volume ratio was to high and temperatures of the solid were unreasonable
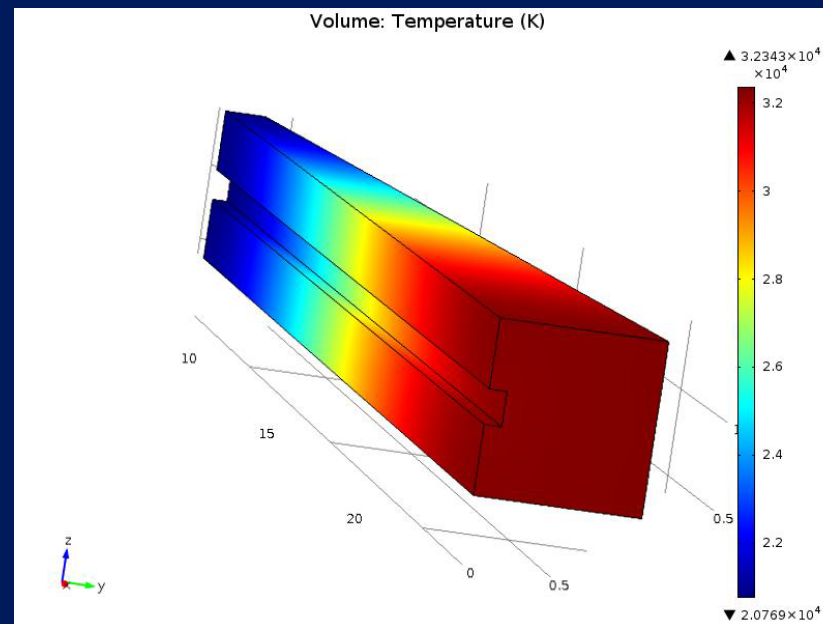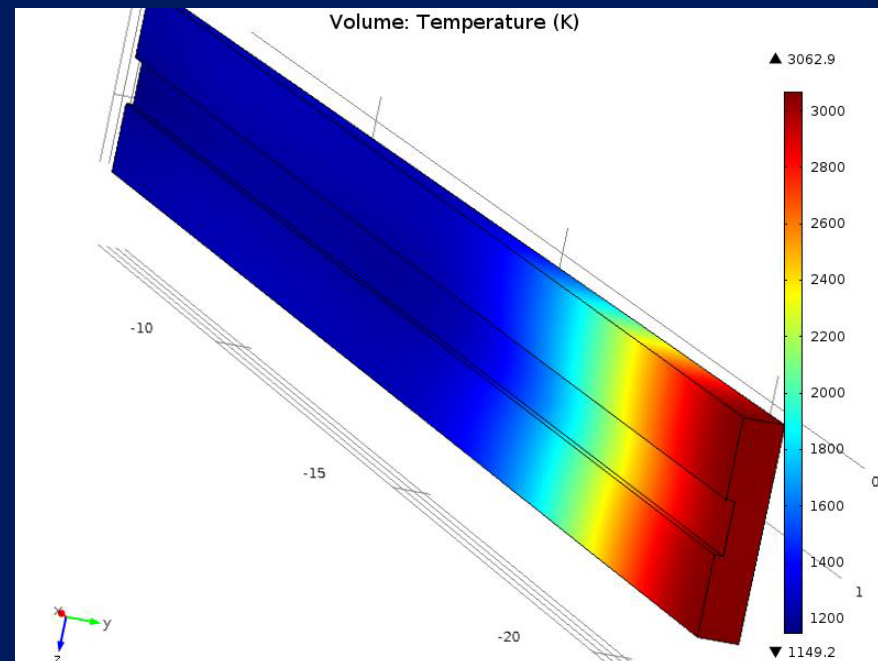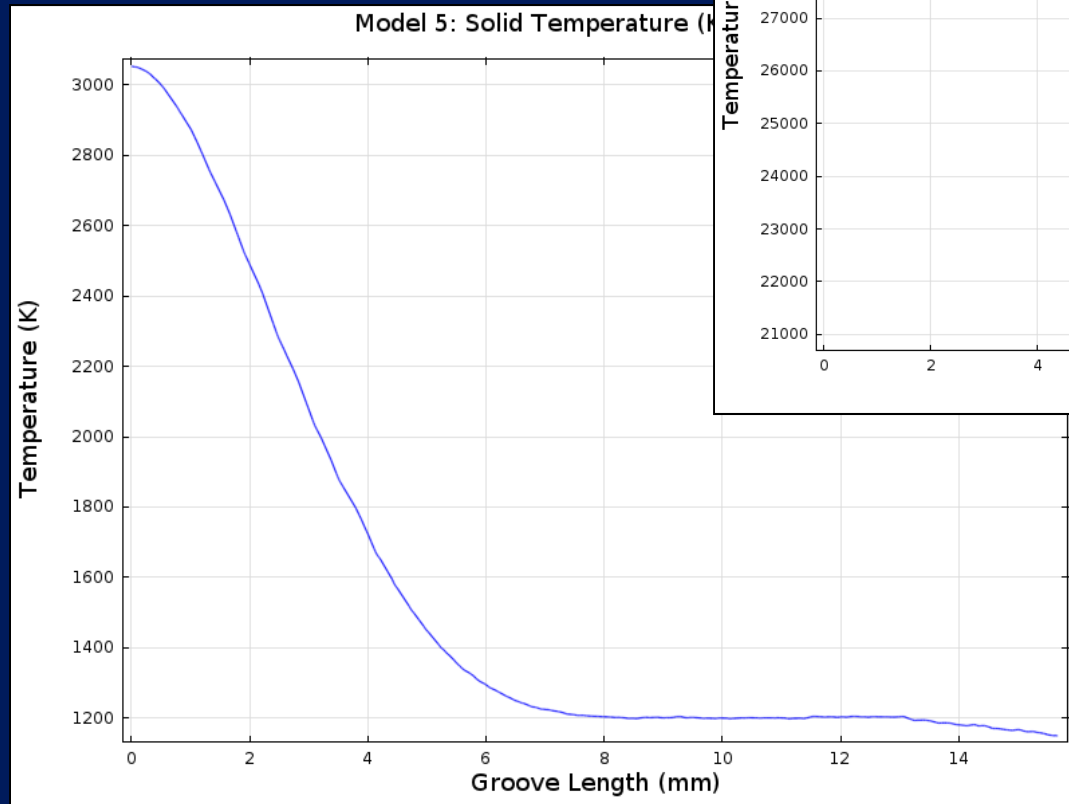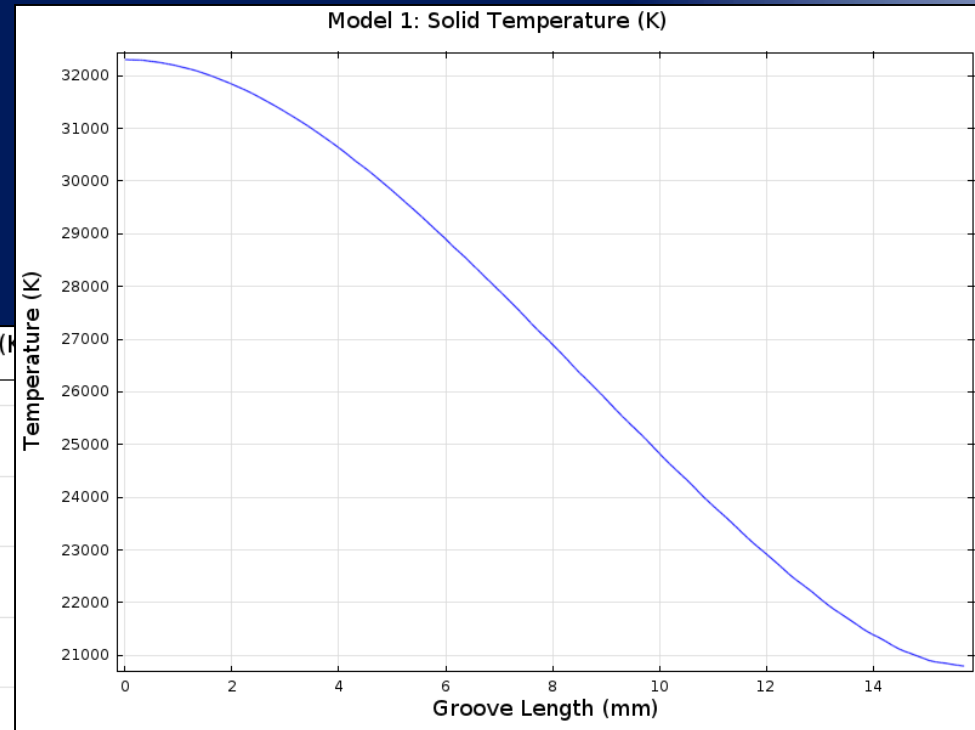

Volume: Temperature (K)

- To decrease the solid volume, more grooves were added
- Flow channels were decreased
- Several models were analyzed to show effects of more channels
- Effects of elongating the channels were also analyzed

Temperature Results

Heat Transfer Results

Table 1: Summary of Heat Transfer Results

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4	360	20	0.25	2784.9	786.80
5	360	22	0.25	3062.6	975.00

As more flow channels are added, solid temperatures become more reasonable.

Results shown are for a 0.01×10^6 Pa (10 psi) pressure drop.

Conclusion

- Many 3D models constructed
- Boundary conditions identified
- Geometric needs identified
- More flow channels will be added for further analysis
- More channels will be analyzed in each analysis
- Disc stack should also be analyzed
- Monte Carlo N-particle (MCNP) code will be used to give more accurate power density data on newer models