A Novel Heat Optimized Oxygen-Deuterium Auxiliary Engine to Re-start the Direct Fusion Drive in Interplanetary Missions

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The Direct Fusion Drive (DFD) is a fusion propulsion method based on the Princeton Field-Reversed Configuration (PFRC) fusion reactor. The high thrust capabilities and the aneutronic nature of the DFD would result in reduced radiation exposure for missions to Mars and beyond. A system to re-start the DFD in space is essential for its use, especially in long-duration missions. Several re-start methods were compared with each other, with the leading solution being an oxygen-deuterium combustion heat engine. This auxiliary engine would generate electric power with the use of thermoelectric generators (TEGs) and steam turbines. The TEGs are provided with the proper temperature gradient by a deuterium-based regenerative cooling outer layer. The resulting steam would be recycled with electrolysis. This heat engine provides an effective method to re-start the DFD while avoiding problems anticipated with fuel cells or batteries. A hydrogen-based version of this heat engine has the potential to be a source of clean energy for terrestrial applications.

I Introduction

Since antiquity, the Moon, the planets, and the stars beyond have captured the imagination of the human race. It is only in recent times that mankind's engineering prowess has caught up with the demand to explore and expand into the vast universe around us. However, we have yet to establish a safe and energy-effective means of transporting either robotic or human crews in interplanetary space. The Direct Fusion Drive (DFD) provides a compelling solution for this task. The DFD is a 1-10 MW nuclear fusion engine that produces both thrust and electric power. The fusion core utilizes a field-reversed configuration with an odd-parity rotating magnetic field heating system to heat the plasma fuel mixture to fusion temperatures. The fuel mixture is of deuterium and helium-3, and additional deuterium is heated in the scrape-off layer for thrust augmentation. Figure 1 illustrates an artist's

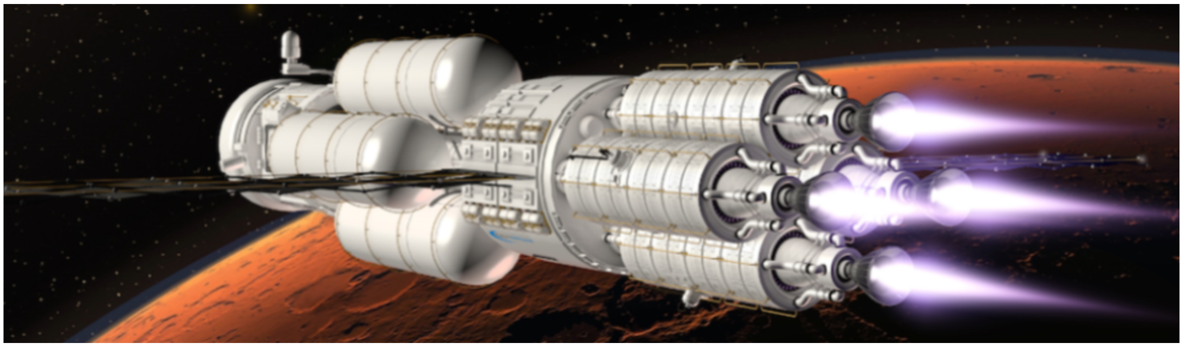

Figure 1: Artist's Rendering of the DFD on a Mission to Mars

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rendering of a vehicle utilizing the DFD on a mission to Mars, according to engineers at the Princeton Satellite Systems. The DFD's efficacy for missions to Mars and other destinations has been studied thoroughly in the past [4, 5]. Prior results have shown that DFD would be able to generate 5 N of thrust per 1 MW of generated fusion power, with an estimated specific impulse of 10,000 seconds. This would result in a greatly reduced mission timeline, significantly reducing radiation exposure and muscle atrophy effects on human crewed missions. The main advantages of the DFD are its very high specific impulse, the aneutronic nature of the fusion reaction, and its ability to produce power for the instruments and crew on board.

Figure 2 displays a diagram depicting the various parts of the DFD engine that make it such an effective propulsion method [5]. In this diagram, there are twelve coils surrounding the fusion core. There are eight field-shaping coils, two next to them that are mirror coils, and two additional ones at the end that make up the nozzle of the notional engine. Woven through these coils are coolant lines that collect the thermal energy from the neutrons, bremsstrahlung radiation, and synchrotron radiation, while also cooling the shielding that protects the coils from the fusion reaction. Additionally, a 1 kW neutral beam injects the fusion fuel into the core of the engine, while propellant enters from the ionizing gas box on the right-hand side of the diagram. Due to the extensive energy requirements to start up these mechanisms, the ability to power on and re-start the DFD in space presents itself as a vital challenge to overcome before it can be readily used as a means of propulsion. A total of 5 MW of power for a duration of 10 minutes has been theorized to be sufficient in starting up a DFD in space, for a total of 3 MJ of stored energy. Past papers on the subject of the DFD speculate on the creation of a start up power unit that would harness the combustion heat energy of the deuterium and oxygen on board, without any elaboration on the design of the power unit [3]. Therefore, this paper will thoroughly present a solution to the start-up problem of the DFD, with the hope that this can be a small step closer to humanity's destiny amongst the stars.

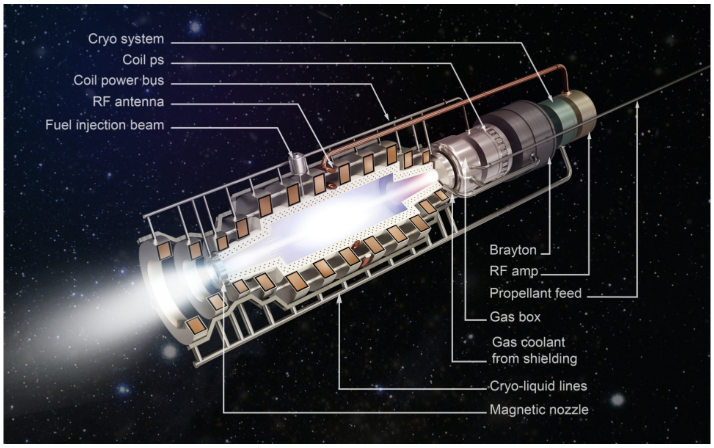

Figure 2: A Schematic Representation of the DFD

II Heat Optimized Oxygen-Deuterium Auxiliary Engine

The task of this auxiliary power unit is to generate a sufficient amount of power with the use of a deuterium fuel and a liquid oxygen oxidizer. The deuterium is already stored on board as the fusion in the DFD is generated by a deuterium and helium-3 reaction. And the oxygen could be recycled from the cabin if this is a crewed mission. After the power is generated, the objective is to eventually split the deuterium-oxide product back into its constituents for use in their respective areas of the spacecraft. This electrolysis can be done after the fusion core is started and there is a sufficient amount of surplus energy from the DFDs. The role of the start up unit as compared to the other major subsystems in the DFD can be identified in Figure 3 [5].

The design of the heat engine first begins with the electric pumps that feed the fuel and the oxidizer into the combustion chamber. A turbopump based feeding system was decided against due to the low mass flow rates that are required for the

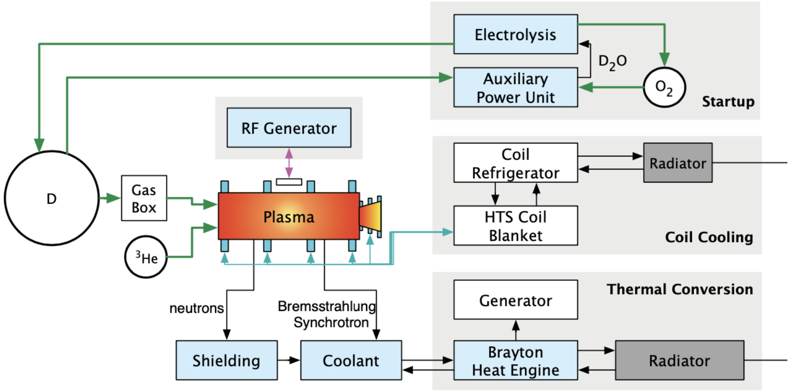

Figure 3: Subsystems Present in the DFD

power generation requirement, the accurate throttle control granted by the use of electric pumps, and the ability to use the power generated by the solar panels to spin the pumps. Before the deuterium fuel is fed into the injector, it is ran across cooling channels surrounding the combustion chamber. This regenerative cooling is performed to heat the deuterium to increase its reactivity, and to lengthen the lifespan of the combustion chamber by minimizing the effect of the high temperature it is operating at. Additionally, the cooling system provides a healthy temperature gradient for the thermoelectric generation layer that is wrapped around the combustion chamber. The oxidizer is directly injected into the combustion from its propellant tank. After passing through the injector and combusting in a successful ignition, the deuterium-oxide steam that is generated is directed towards a turbine system. The turbine system and the combustion chamber are attached with a flange. The turbine system consists of two sets of blades that are separated by a disk that asks like a stator in a steam turbine. The exhaust is first directed towards a doughnut shaped casing that allows for the heavy water steam to hit the blades in a direction that is parallel to the blade disk's central normal axis. The two turbine disks are attached to a common axis that extends outside the casing that contains the turbines. The rotation of this axle is then used to generate power with an electric generator. Finally, the steam then exits through a large exhaust manifold tube that directs it to a temporary storage container. A CAD model of the entire design of this system, excluding the electric pumps, can be seen in Figure 4.

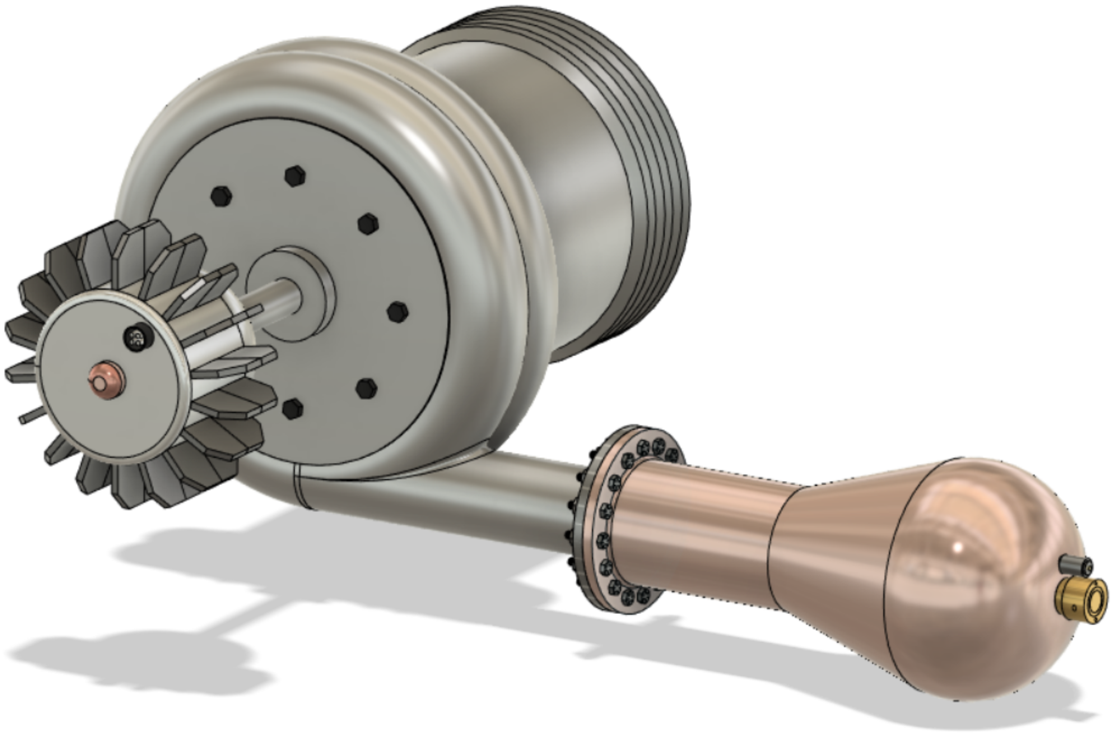

Figure 4: CAD Model of the Heat Engine

III Injector Design

In order to inject the deuterium and oxygen into the combustion chamber, a coaxial swirl injector will be used. The injector is designed to have a central opening for the oxidizer and two smaller openings closer to the outer perimeter for the fuel. The oxidizer is flown through the injector in a manner that swirls the liquid into the combustion chamber, yielding a conical spray of oxidizer. This conical release of oxidizer increases the cross section of the fuel and oxidizer reaction. The intake holes of the oxidizer are at a shallow angle to the main oxidizer inlet, giving the oxidizer its swirl flow. The cross sectional view of the injector and its CAD model are displayed in Figure 5 and Figure 6. Based on the experimental evidence, a more robust version of this injector with more inlet holes may have to be implemented to attain the necessary energy production values. A pintle injector design was considered for its throttle capabilities, however sufficient throttle control can be obtained from the electric pumps. This relieves the complexity of further control at the injector. Additionally, the use of a coaxial swirl injector aligns with the current space industry standards for hydrogen fueled engines. A spark ignitor is placed closely above the injector, in order to provide the sufficient ignition temperatures needed to start the reaction. This ignitor is visible in Figure 4. In the case that an array of such injectors is needed, the ignitor will be placed in the center of the injectors. Finally, the material of the injector is recommended to be an oxygen-free copper alloy. An oxygen-free alloy will prevent any unwanted impregnation of oxygen into the mixture. Copper seems to be the ideal choice here due to its high thermal conductivity and high melting temperature.

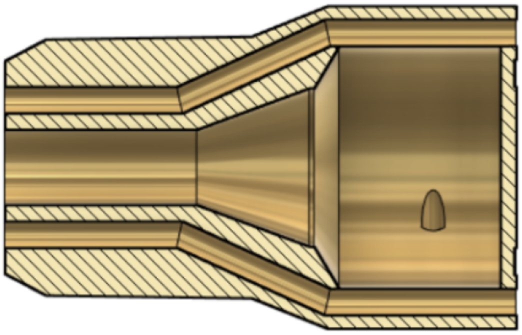

Figure 5: Injector Cross Sectional View

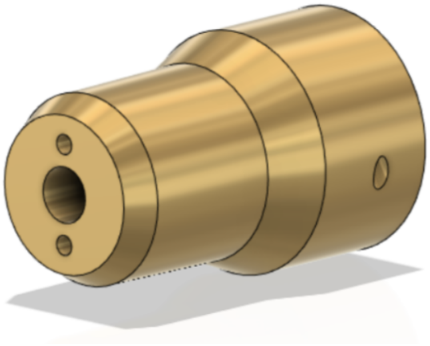

Figure 6: Injector CAD Model

IV Combustion Chamber

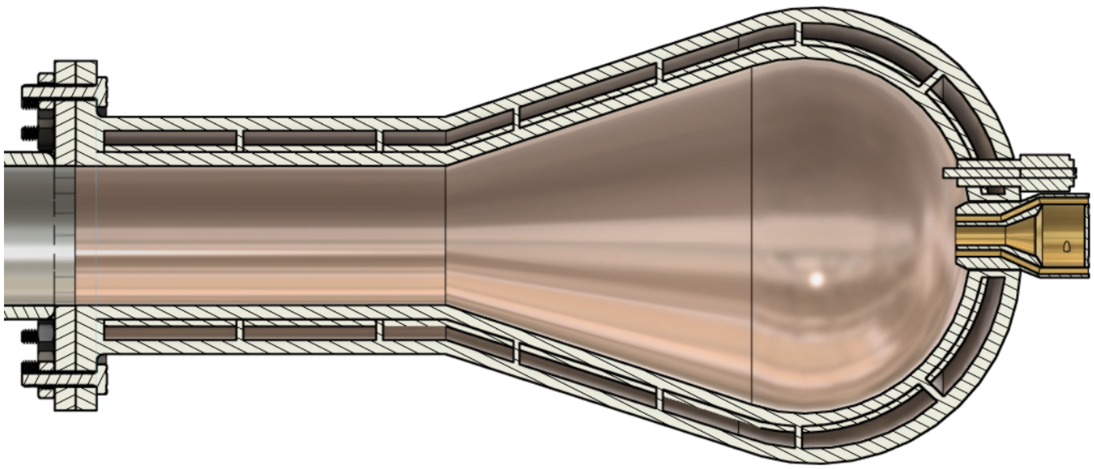

Figure 7: Cross Sectional View of Combustion Chamber

The combustion chamber is where the Deuterium and the Oxygen will react to produce the heavy water steam. Most of the chamber is made of the same copper alloy as the injector. One can see the cross sectional view of the combustion chamber in Figure 7. Within Figure 7, the gaps that surround the main chamber are part of the regenerative cooling process involved in the combustion chamber design. Deuterium flows through these channels before being injected into the combustion chamber. This process of running cryogenic Deuterium across the surface of the chamber provides a heat sink for the combustion reaction occurring within the chamber. This protects the material of the chamber from melting or deteriorating over time. Additionally, this act of regenerative cooling heats the fuel to a higher temperature, allowing for a more reliable combustion reaction. Finally, between the cooling channels and the surface of the combustion chamber lies a thermoelectric generation layer. This layer of electrolytic material generates power from the heat gradient present between the Deuterium fuel and the hot combustion within the chamber. The steeper this gradient, the more efficient the thermoelectric generation, therefore, the cryogenic Deuterium also aids in this power generation. Furthermore, the geometry of the combustion chamber has yet to experience experimental validation. Therefore, based on the pressure and temperature requirements of the turbines, the exit diameter of the chamber and the volume of the chamber may need to be adjusted. Finally, thermo-acoustic instabilities, or combustion instabilities, are a concern when evaluating combustion chamber design. The damage of these instabilities amplifies with their ability to excessively vibrate the system that contains them. Therefore, in order to limit the propagation of any heavy vibrations created within the chamber, a more absorbent connection point between the combustion chamber and the turbine system may need to be contrived to replace the flange. Additionally, live feedback of the state of the combustion can be fed into the control loop of the electric pumps in order to limit any harmful effects of these instabilities.

V Thermoelectric Generation Layer

The bottoming cycle of this heat engine will be this thermoelectric generation layer that lies on the surface of the combustion chamber. This process of converting the waste heat of the combustion reaction to power will increase the thermal efficiency of the engine. Researchers from the Massachusetts Institute of Technology (MIT) have recently published their experimental demonstrations of thermophotovoltaic (TPV) cells that match the characteristics of this thermoelectic generation layer. The TPV cells are optimized to operate under 1,900 to 2,400°C, the same temperature ranges that will be experienced by this layer [1]. Additionally, these cells have a thermal efficiency of around 40 percent in this temperature range, which is higher than most traditional steam turbines [1]. This effective form of waste heat recovery will maximize the power production of the heat engine.

VI Turbine System and Electric Generator

The Deuterium-Oxide, or heavy water, steam produced within the combustion chamber is directed towards the turbines. The turbines then operate similarly to a traditional steam turbines that are ubiquitous within the energy production sector. The inlet into the turbine chamber directs the steam to a doughnut shaped enclosure that allows the steam to flow through the turbines in a direction parallel to the turbine disk's central axis. There are two sets of blades within the turbine chamber, and these two sets are divided by a disk that acts like a stator. This stator limits the flow of the steam from one turbine to another, in order to increase the pressure that the second turbine receives. This is done to maximize the work output of the exhaust of the combustion. The geometry of the turbines and the design of the turbine chamber has yet to be optimized with rigorous simulations or experimental data, yet the first turbine is displayed in Figure 8, the cross sectional view of this chamber. The two turbines share a common axle that combines the work output of the turbines. This axle is attached to an electric generator that is placed outside of the chamber.

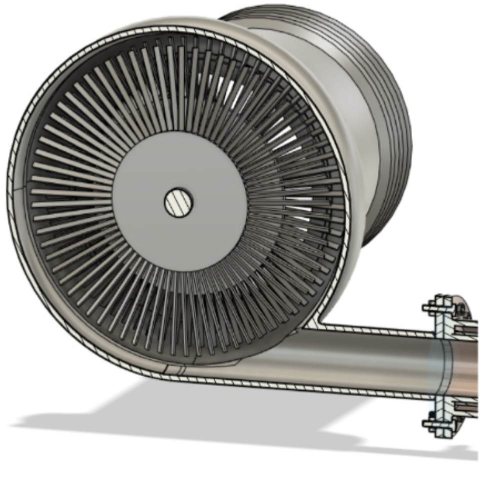

Figure 8: Turbine Chamber Cross Sectional View

An artist rendering of this generator is visible on the left side of Figure 4. There will be cooling fins on the outer surface of the generator that will increase the exposed surface area of the module. This increased surface area will increase the radiative cooling that will occur in the vacuum of space. This generator will then be the power source of the DFD, along with the power generated by the thermoelectric generation layer. Finally, the exhaust of the heat engine is directed away from the turbines and into a temporary storage chamber. This steam will eventually be converted back into its constituents when there is enough surplus energy from the DFD fusion reaction. The exhaust pipe is the larger opening visible in Figure 4. The volume of this exhaust manifold is designed to compensate for the increased volume of the steam and as a source of low pressure to increase the flow through the turbines. Additionally, in order to adjust to the changes in temperature the metal faces, the pipe has the ability to fold and expand.

VII Mass and Combustion Properties

Mass calculations were performed to estimate the mass of the heat engine. The masses of off-the-shelf components that make up the heat engine were utilized for this measurement. Parts such as a 600 Watt electric generator, and a supercharger that includes turbines and a casing were found. The mass of the combustion chamber was calculated with the Fusion 360 CAD software that it was modeled in. The mass calculation includes the density of the design and the estimated volume of the heat engine.

The mass of the electric generator that satisfies the power requirements came out to be around 8.35 kilograms. The mass of the supercharger, which is commonly found in car engines, came out to be around 8.50 kilograms. This supercharger is made up of heavy and heat-protective material, and it acts as a valid heuristic for the final turbine chamber in the heat engine. Finally, the mass of the combustion chamber output by the CAD software has an estimation at around 25 kilograms. The estimated mass of the heat engine then totals to be 41.85 kilograms. This is a small fraction of the total dry mass of the DFD at 28,581 kilograms [2]. Additionally, this low weight aligns with the mass optimization required with the high per-kilogram costs of orbital launches.

In order to investigate the combustion properties of the Deuterium and Oxygen reaction, the experimental evidence and the literature describing the combustion between Hydrogen and Oxygen were used. Deuterium, being an isotope of Hydrogen with an extra neutron, did not have any past research investigating its combustion chemistry with Oxygen. Additionally, it was calculated that the difference in the free energy of formation between the two processes was 0.03 percent, a small enough difference to make a comfortable switch to Hydrogen and Oxygen combustion dynamics. The only significant difference between the two combustion processes was that the Deuterium one is slower due to its heavier atomic mass.

The energy production of the reaction between Hydrogen and Oxygen is 286 kJ per mole of Hydrogen burned. With a molar mass of 2.016 grams per mol, the heat released per kilogram of Hydrogen is 141.87 MJ. The experimentally evident upper limit of the stored energy in a start-up of a PFRC is 3 MJ, with a time of about 10 minutes to get there. This would require an electric generator to be capable of at least 500 watts. Additionally, with 3 MJ of stored energy required, at least 0.021 Kg of Hydrogen must be burned with the energy density above. And with the molar ratio of 0.5 moles of Oxygen for every mole of Hydrogen, at least 0.167 Kg of Oxygen is needed for this energy production. These estimations are assuming a heat engine that is 100 percent efficient, therefore, these mass values will only increase with lower efficiency. These calculations are also assuming that you are only powering on one DFD and the power generated from that is being used to start the rest of the DFDs on board the spacecraft.

Extra propellant mass can be found in the pressurizing agent in the tanks. In order to prevent cavitation at the pumps, and gain additional control over the flow of the propellants, the Helium-4 generated in the heat exchanger in the DFD can be used as a pressurizing agent in the propellant tanks. Throughout the space industry, Helium is often used as a pressurizing agent, pushing the liquid fuel and oxidizer into the combustion chamber, by virtue of its inertness and low boiling and melting temperatures. The necessity of using Helium-4 to purge the system of any combustible gases before activation of the heat engine has not shown promise to be worth the complexity and extra propellant weight.

VIII Fluid Simulation Results

Preliminary simulations were performed on the design of the heat engine on Ansys Fluent. Due to the computational limitations and the limited access to Ansys granted by the student license, the simulations were performed on a 2D slice of the heat engine with limited depth of the initial conditions. The objective of these rudimentary simulations was to examine the presence of any significant hot spots in the temperature within the chamber and to study the pressure flow to the turbines.

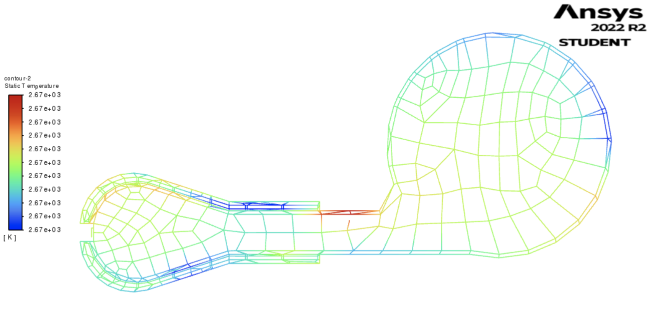

Figure 9: Temperature Fluid Simulation

Figure 9 displays the temperature gradients present in the fluid simulation. The temperature differences at the walls of the combustion chamber are of significance due to the thermoelectric generation layer and the effort to increase the longevity of the heat engine for long-term space missions. Additionally, the temperatures within the chamber that impacts the turbines are of value as high temperatures can damage the blades. The only significant hot spot visible in this low-resolution simulation is the top wall right before the opening to the turbine. This problem may be resolved by adjusting the internal or exit geometry of the combustion chamber so that the heat is more evenly mixed within the reaction and diverted away from the walls.

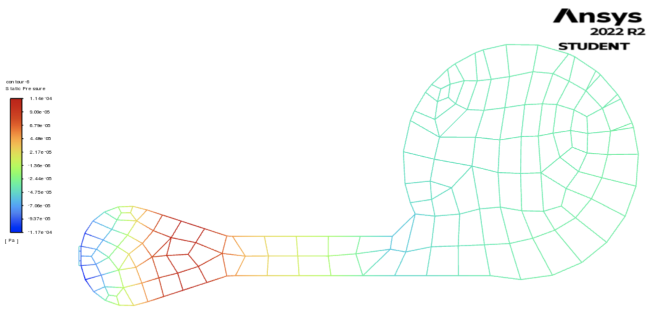

Figure 10: Pressure Fluid Simulation

Figure 10 displays the pressure gradients present in the fluid simulation. One can identify the high pressure region of combustion on the later half of the combustion chamber. It is vital to divert a healthy portion this pressure towards the turbines so that the engine can output as much work from the exhaust as possible. The physics of the combustion, including the characteristic velocity of the propellants, the specific impulse, and Bernoulli's principle can be used to optimize these factors before experimental data. Additionally, a more robust injector can generate a more refined combustion, however the designed injector was not included within this simulation.

IX Comparison To Other Solutions

When considering the design of the heat engine, it is important to compare this solution with the alternative methods that could be used to start up and re-start the DFD. The two other methods that were weighed as options were batteries and fuel cells. These methods of power generation are common in the space industry. The space shuttle used three alkaline fuel cells to satisfy all electrical power requirements from pre-launch to post-landing, and the Apollo missions also used fuel cells on their trip to the Moon. And spacecraft, such as the International Space Station, that use solar arrays always carry batteries for their power requirements. While batteries, fuel cells, and this heat engine can all provide the sufficient energy required, the drawbacks of the batteries and fuel cells make the heat engine the most compelling option. The electrolytic material within the fuel cells and batteries makes them prone to radiation damage. While there is radiation-sensitive material within the thermoelectric generation layer on the combustion chamber, the main source of power is from the turbines. Additionally, fuel cells have too low of a power discharge rate to be effective in powering on a DFD. And in regards to batteries, they have too low of a lifespan for long-term space missions, and they are not weight-efficient for the power they provide. Finally, if the plan was to stick to precedence and carry an Alkaline Fuel Cell (AFC), then due to AFCs being sensitive to Carbon Dioxide impurities, it will be difficult to recycle the air from the cabin for Oxygen. Even though this heat engine is the most complex solution, the drawbacks of the alternative options make it the most promising choice.

X Conclusion

This paper presents the design of a heat-optimized auxiliary engine that has the ability to start up and re-start the DFD in interplanetary space. This auxiliary heat engine is a vital component to the DFD propulsion system. The preburner fed turbine design that this heat engine utilizes has the potential to be used in terrestrial applications when fueled with Hydrogen. Especially considering the abundance and high energy density of Hydrogen, and the clean emissions that the engine produces. A significant amount extensive work still needs to be put into the creation of this engine. However, this paper presents itself as a good first step in the right direction towards this engine's small but significant role in humanity's journey to the Moon, Mars and beyond.

XI Acknowledgement

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