5-2-2023

A Proof-of-Concept Study for an Elastohydrodynamic Seal Design

Cameron M. Stuart
Georgia Southern University

A Proof-of-Concept Study for an Elastohydrodynamic Seal Design

An Honors Thesis submitted in partial fulfillment of the requirements for Honors in Mechanical Engineering

By

Cameron Stuart

Under the mentorship of *Dr. Sevki Cesmeci*

ABSTRACT

Supercritical CO_2 (sCO_2) power cycles are superior to traditional water based, air-breathing, direct-fired, open Brayton cycles or indirect-fired, closed Rankine cycles in terms of efficiency and equipment size. They hold great potential in fossil fuel power plants, nuclear power production, solar power, geothermal power, and ship propulsion. To unlock the potential of sCO_2 power cycles, utilized technology must withstand 10–600 MWe and at sCO_2 temperatures and pressures of 350–700°C and 20–35 MPa for nuclear industries. Amongst many challenges at the component level, the lack of suitable shaft seals for sCO_2 operating conditions needs to be addressed. So far, conventional seals all suffer from the incapability of handling sCO_2 pressures and temperatures in one way or another. These seals suffer from high leakage rates, bristle wear, and scalability constraints. There is a worldwide effort to develop effective sealing technologies for sCO_2 turbomachinery. This research focuses on creating a proof-of-concept alternative seal design that can potentially be used in sCO_2 turbomachinery. The seal will be demonstrated on a larger scale; utilizing water flowing through a chamber and studying how the pressure gradient and seal deflection affects the performance of the seal. Under these conditions, if the pressures at the top and bottom of the seal are constant and decreasing along the flow path, respectively, then the seal will deform in a way that forms a throat towards the root of the seal. In this work, an experimental methodology has been developed, including the instrumentation and fabrication of the components.

Thesis Mentor: ________________________

Dr. Sevki Cesmeci

Honors Dean: ________________________

Dr. Steven Engel

May 2023

Department of Mechanical Engineering

University Honors Program

Georgia Southern University

Acknowledgements

I would like to start by thanking my research mentor, Dr. Sevki Cesmeci, and his research students who made this research project possible. Their guidance and assistance through this project have pushed me to put my best foot forward and keep on pushing on, no matter what difficulties I may encounter.

I would also like to thank the Mechanical Engineering Department, the College of Engineering and Computing, the Department of Energy, and the University Honors Program. Without them, I would not have had the knowledge, funding, or equipment necessary to make it where I am.

Thank you to the friends I have made along the way; namely Ana Abadie, Matthew Adharsingh, Trevor Carlton, Adam Head, Kody Pierce, and Garrett Sydnor. They were always there for me when I needed them most and were there to share a laugh.

I would like to thank my high school teachers, Mr. Mercier and Ms. Davis for introducing me to the FIRST Robotics program. FIRST inspired me to pursue the field of mechanical engineering and created a family away from home for me. Best of luck to FRC teams 3329 and 8815 in the future.

Finally, I owe a tremendous amount of gratitude to my family. My parents, sister, and brothers have always pushed me to be the best person I can be and to make a difference in everything I do. I can undoubtedly say that none of this would have been possible without them, nor would I be the person I am today.

Thank you all for what you do.

Introduction

Supercritical carbon dioxide (sCO_2) cycles were initially to be implemented into nuclear energy production in the 1960s and 1970s but were soon disregarded as light water reactors' core exit temperature are too low and cannot operate under high pressures, making the system incompatible for supercritical carbon dioxide [1]. Since the 2000s, supercritical carbon dioxide power generation has reemerged due to the development of the Generation IV nuclear reactors which operate on a higher temperature, allowing for a high factor of safety to be met. Supercritical carbon dioxide systems utilize carbon dioxide in its critical state as opposed to steam, or any other fluid, because when carbon dioxide is held above its critical temperature and pressure it still has the density of a liquid but behaves as a gas [2]. Supercritical carbon dioxide power generation has since been viewed as a promising alternative to energy production in nuclear, solar, fossil fuel, etc. due to its higher thermal efficiency and lower cost than most conventional steam power production systems [3]. Compared to helium and steam, supercritical carbon dioxide yields the highest efficiency when the turbine inlet temperature is above 550℃.

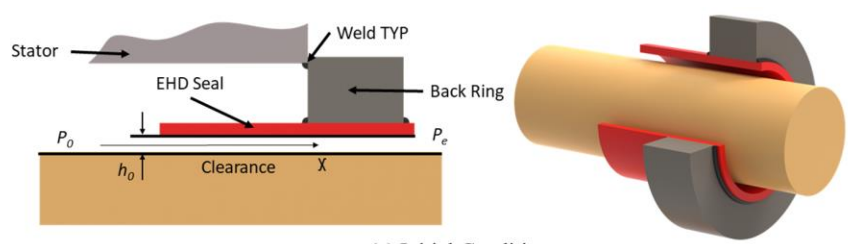
Supercritical carbon dioxide power generation systems have been widely developed nowadays, but due to the expansive implementation of it, a few notable points of failure have been observed. One of the downsides to this process is that there is a high amount of leakage within the system. There is not any existing, reliable seal technology to prevent the fluid from escaping the system [4]. In Bidkar's, Sevincer's, Wang's, Thatte's, Mann's, Peter's, Musgrove's, Allison's, and Moore's [5] research they utilized conventional end seal technology which resulted in an accumulated leakage mass flow of 0.1kg/s-0.15kg/s, which is about a 0.6-0.8% decrease in cycle efficiency [2]. Existing seal technology must be experimented with to design a seal that will provide the most efficiency to the system.

There have been various approaches taken to ensure that the forces being endured by the seal are kept at a minimum as to not negatively affect the flow of the fluid through the system, as seen in such cases where there is leakage, recirculation, damage to the seal, and undesirable changes in fluid properties at the given point(s) [6]. In extreme cases, where a pump has been used for an extended period under increasing/strong forces, Tan, Lu, Wu, Liu, and Tian [7] noticed that there will be anomalies and potentially even cracks within the seal of the pump, which will ultimately cause the entire system to fail once the seal has reached its limits. The method of analyzing seals for such occurrences is through vibration signaling and can help detect a problem within the system before a catastrophic event occurs, as demonstrated by Luo, Zhang, Fan, Han, Li, and Acheaw [8]. Through this research project the optimal seal, subjected to predetermined conditions, will be tested to see how the forces/pressure on the seal changes as the clearance of the seal is adjusted.

This research focuses on creating an experimental test rig to see what is happening to the seal on a larger scale. Building this system on a larger scale will help give a visual indication of what is happening to the seal in existing technology. Water will be utilized as opposed to supercritical carbon dioxide to show the proof-of-concept of why and how the seal in the system deforms. As the fluid flows below the seal the pressure will gradually decrease as it travels along the length of the test rig while the pressure above the seal is kept constant, creating a distributed load on the seal. If the pressures at the top and bottom of the seal are constant and decrease along the flow path, respectively, then the seal will deform in a way that forms a throat towards the root of the seal.

Methodology

The primary factor when it comes to designing and testing this system is understanding why the seal deflects. Due to the functions of the pump, the pressure of the water flowing out of it will be at an increased pressure than what it was before it entered the pump. As the water continues to flow out of the pump and into the test rig, the pressure will start at a high, but then gradually decrease in pressure. This is due to the way in which fluids move, from a high pressure to a low pressure. Figure 1a demonstrates how the seal is attached to the back ring and sits on a rotor that has a clearance of h_1. Upon the rotor ramping up to speed $P_1 >> P_2$ there is a uniformly distributed pressure load, causing an inward deformation, allowing for leakage to accelerate. Due to the upstream pressure always being higher than the downstream pressure, the clearance in the throat will never be zero. This occurs due to the pressure gradient that appears on one side of the seal while the other side is kept at a constant pressure, which creates a surface force that occurs due to the presence of a pressure gradient. The deflection is notable enough to create recirculation in the flow of the fluid which decreases the efficiency of the system.



(a) Initial Condition

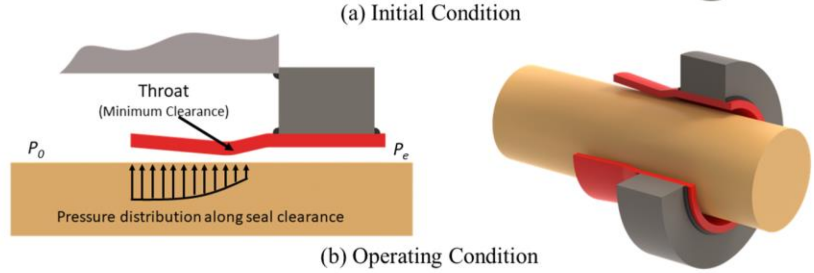

(b) Operating Condition

Figure 1: EHD Seal Concept

Cesmeci et. al. [9,10] conducted simulations on a two-dimensional axisymmetric model, as given in Figure 1, utilizing nitrogen for the fluid and structural steel for the solid. These simulations were performed in the software COMSOL in which a fluid-solid interaction was performed. Two approaches were taken, one way coupling and fully coupled. In one way coupling the fluid data was transferred to the solid domain which was then used to determine the deformation of the seal. Fully coupled simulations solved the flow region using the Reynolds equation where the fluid data was then sent to the solid domain. After solving for the solid domain, the deformation data was sent to the fluid region and vice versa until the simulation converged.

The simulation results are depicted in Figures 2-7 [10]. The images and graphs depict a comparison between the one-way coupling and two-way coupling results. The film thickness experienced is depicted in Figure 2 [10]. The film thickness is a behavior of the fluid that tends to stick to the walls in which it is flowing due to the viscosity of the fluid and the velocity profile still developing. Figure 3 demonstrates the von Mises experience [10]. This shows the areas of low and high fatigue within the system, with the highest stress centralized at the fixed end of the seal. Figure 4 showcases the analytical results of the effect of pressure on the clearance of the seal [10]. From this, it is evident that as the pressure increases the clearance length also increases; this causes more wear and lack of efficiency for the system. Figure 5 serves as a comparison between the results obtained for one-way coupling and fully coupled systems [10]. These graphs show the fully coupled system is affected more by a change in pressure, but at the fixed end of the seal the behavior between the one-way coupling and the fully coupled system is comparable. Figure 6 shows the difference in mass flow rate between the one-way coupled and fully coupled system

[10]. These results demonstrate that there is a higher mass flow rate for the one-way coupled system compared to the fully coupled system. Finally, Figure 7 shows the radial displacement of the seal based on a varying pressure [10].

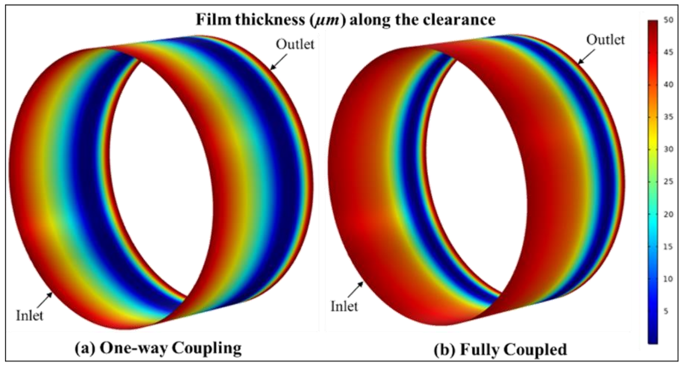


Figure 2: Simulation Results: Film Thickness [10]

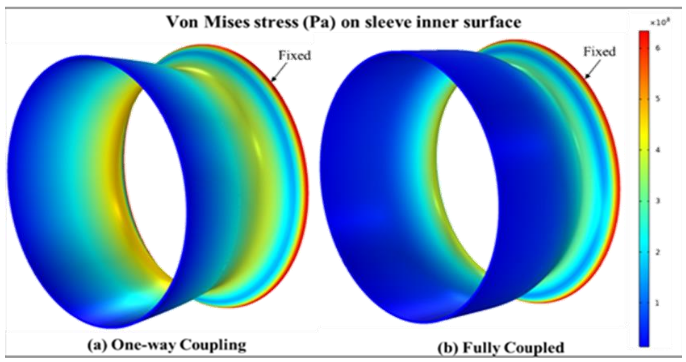


Figure 3: Simulation Results: Von Mises Stress [10]

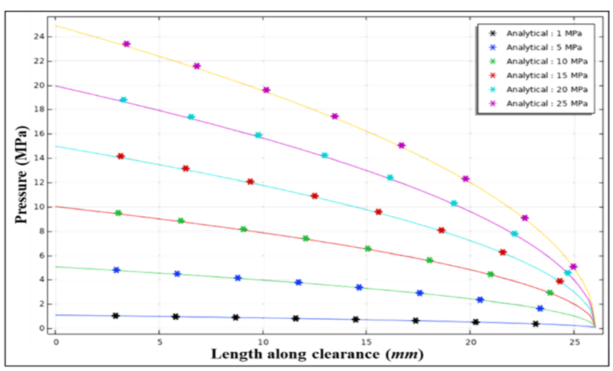


Figure 4: Analytical Results of Pressure Effects on Clearance [10]

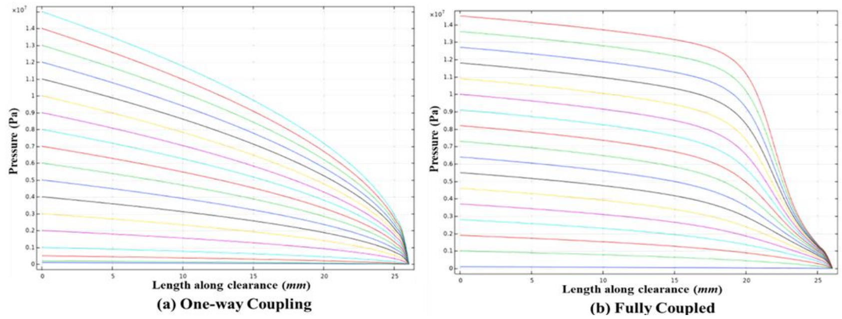


Figure 5: Simulation Results: One-Way Coupling & Fully Coupled Pressure Variation [10]

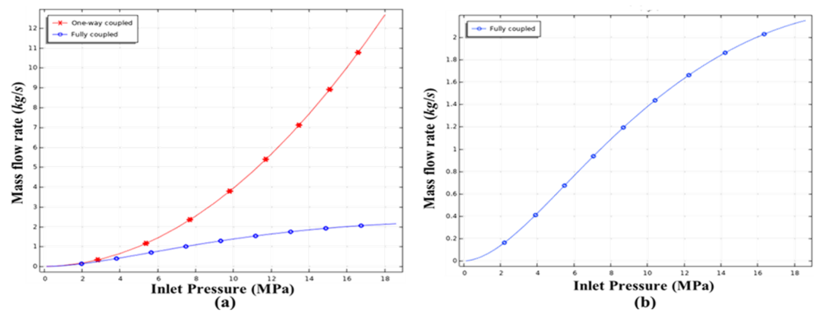


Figure 6: Simulation Results: One-Way Coupling & Fully Coupled Mass Flow Rate [10]

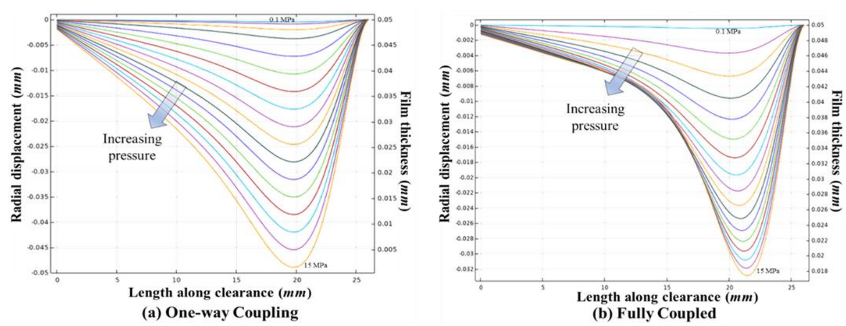


Figure 7: Simulation Results One-Way Coupling & Fully Coupled Radial Displacement [10]

The simulation results confirm the proposed hypothesis in that the pressure variation along the length of the seal causes it to deform the most at its free end compared to the fixed end. It is also beneficial to prove the hypothesis through the conduction of a physical experiment and so the experimental apparatus was focused on. The test rig for this experiment will be mounted atop an F1-10 hydraulics bench, manufactured by Armfield. This hydraulics bench utilizes a submersible circulating pump which provides a max head of 8.3m H_2O [11]. The max head can be converted into pressure and yields a max value of approximately 81.4kPa or 11.8psi. The hydraulics bench also allows for water to be reused by recirculating it. Water will enter the test rig after being sent out of the circulating pump and after leaving the test rig it can be redirected to flow into the volumetric tank and repeat the process over again. The volumetric tank allows for a max flow of 80 liters/min without the appropriate accessory and 100 liters/min with the appropriate accessory. The F1-10 hydraulics bench and pump used can be seen in Figure 8 and Figure 9.

Figure 8: F1-10 Hydraulic Bench

Figure 9: Circulating Pump

A circulating pump, which is a type of centrifugal pump, will be used to push the water through the proposed test rig. Centrifugal pump systems are used to increase the pressure of a given fluid by applying velocity energy to it which is then converted to pressure energy [12]. Typically, this fluid is only that of a liquid because most gases are compressible which makes it harder to obtain the same results as if a compressor were used. When this liquid flows out of a pump there will be some form of deformation on the walls of the flow path due to the pressure gradient between the outside and inside surfaces of the flow channel. This can create an issue in some high-end, precise systems, like in existing supercritical carbon dioxide systems.

Bachus and Custodio [13] explain how centrifugal pumps work; they go on to say centrifugal pumps work by taking in the fluid at the nozzle which is then funneled into the pump housing and into the impeller. The impeller is connected to a shaft which spins as a result of being connected to a motor. The impeller blades trap the fluid in the eye of the impeller which increases the velocity of the fluid as it travels to the outer diameter of the impeller. This increased velocity results in a lower pressure at the eye of the impeller. Bachus and Custodio conclude that the fluid can then leave the impeller's outer diameter at a high speed and slam into the casing wall of the volute which converts the velocity to pressure, which follows the Bernoulli Principle [13]. While this is evident based on the functionality/design of the centrifugal pump, studies utilized laser doppler velocimetry and particle image velocimetry to verify that the fluid flows in this manner with a transparent pump in order to see how the fluid moves within the impellers and diffusers of the pump [14].

An important part of this experiment is selecting the proper pump to increase the pressure of the fluid to an experimental pressure. Part of this consideration is by analyzing the losses the fluid will endure as it travels through the system, through head loss which relates to the roughness of the channel [15]. After flowing through the pump, the water will need to flow through a pipe network, through an adapter from the pipe to the channel inlet that has the seal and then back into another pipe system to flow back to the inlet of the pump. When selecting the pump to carry out this experiment it is important to ensure that the power supplied to it is enough to run the pump at its highest efficiency and ensure that a large enough pump is chosen so the inlet pressure satisfies the pressure required rather than cutting short [16].

Results

The test chamber for this research is designed to take fluid from the pump in on one end and goes through the exit where the seal is mounted above the clearance. This will cause the seal to deflect based on the pressure gradient apparent throughout the system. To experimentally demonstrate the deflection of the seal a test rig had to have the following components: an inlet and outlet for the water to flow through the system, a transparent wall material as to see if the pressure gradient made a noticeable impact on the seal material, the seal, which would deform due to the change in pressure, and durable reinforcements to ensure the test rig would not collapse on itself. Considering these factors, the test rig was designed with the aid of SOLIDWORKS and went through multiple iterations as the topic was understood at a deeper level and operating and measuring equipment were considered. Figure 10 displays the first iteration of the test rig.

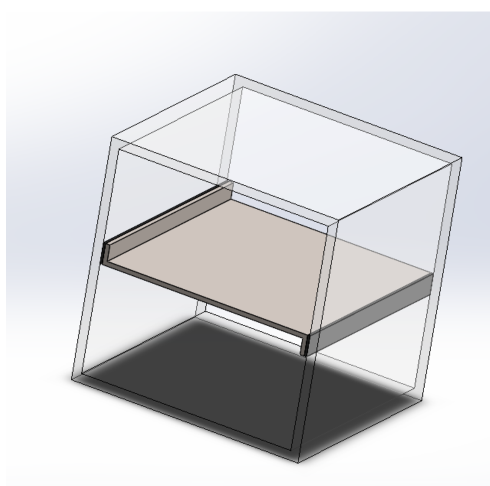


Figure 10: Initial Test Rig Design

In this design, the high-pressure water would flow over the top of the seal while a constant, atmospheric pressure would be along the bottom. The seal would be mounted along the sides of the polycarbonate test chamber with neoprene strips between the two to limit leakage into other parts of the chamber. While this design is a good conceptual starting point, it is not adequate enough to obtain the results necessary as there is not a free end of the seal to deform.

The second design for the test rig, as shown in Figure 11, includes the same channel as the initial design and improves upon it by implementing an inlet and outlet and allows for the seal to be manufactured at varying lengths. Due to the complexity of the inlet and outlet caps, they are designed to be manufactured out of polylactic acid, PLA, which is a 3D printing material. 3D printing these caps would allow for the manufacturing process to be less time consuming and less expensive but would not be waterproof. Due to the printing process and structure of PLA it is permeable to water and would not be able to withstand the water pressure going in and out of the test rig. To overcome these obstacles the inlet and outlet could be cast or designed with simpler geometries rather than having a loft. The casting process would ultimately take more time and experimentation to perform successfully and thus led to the decision to make the design have simpler geometries.

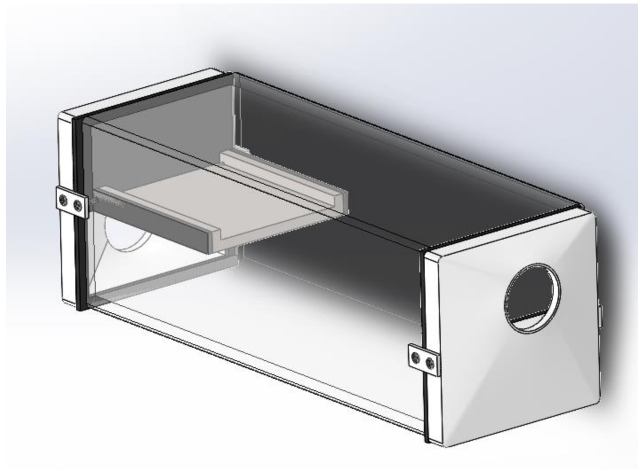


Figure 11: Second Test Rig Design

Another point of improvement with this design is the lack of reinforcement for the inlet and outlet. The bracket for the inlet and outlet would connect the to the polycarbonate, but would likely result in the material cracking due to the assembly process. Additionally, more brackets would be necessary along all sides of the test chamber to ensure the inlet and outlet caps are not forced apart from the polycarbonate due to the pressure within the test rig. With all of these points of improvement noted, a third design was created to diagnose these issues.

The third test rig design, as shown in Figure 12, implements a mounting system for the fixed end of the seal and improves upon the previous design by adding an all-thread rod between the inlet and outlet caps. In addition to this, the fasteners previously intended for the inlet and outlet caps were replaced with a weld. By doing these things, the test rig will be able to withstand the pressure inside and the seal will deform as intended. This design allows for external systems to be connected and for the desired results to be collected and analyzed, but lacks the appropriate fasteners to keep the inlet and outlet plates connected to the all-thread and a mounting system so the test rig can be mounted on a surface.

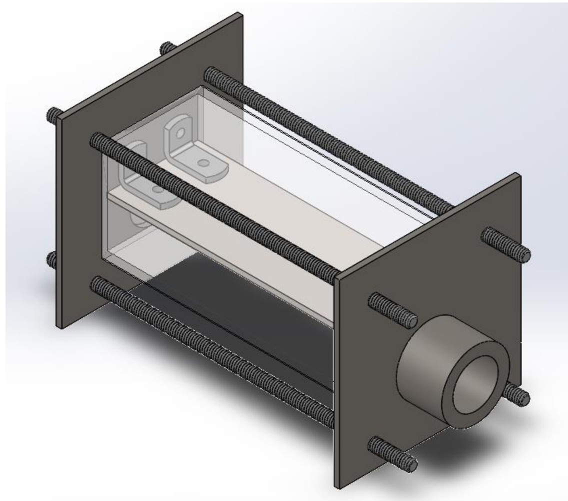


Figure 12: Third Test Rig Design

The fourth and final test rig design expands upon the last by incorporating mounts, fasteners, and attachments, as seen in Figure 13. All components, other than the seal, are made out of stainless steel which allows them to hold up to the oxidation, corrosion, and high pressures and forces they could be subjected to. The test rig is capable of being connected to an outside source and rested/mounted on a flat surface, like that of the F1-10 hydraulics bench mentioned earlier. Figures 14-16 show the test rig from the front view, side view, and top view, respectively.

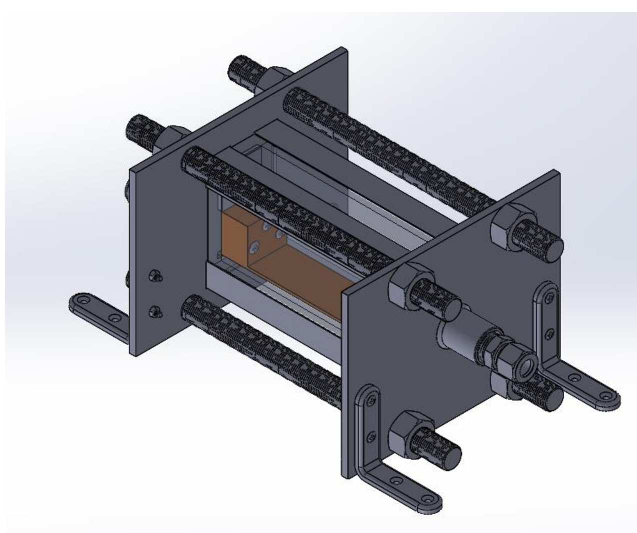


Figure 13: Final Test Rig Design CAD

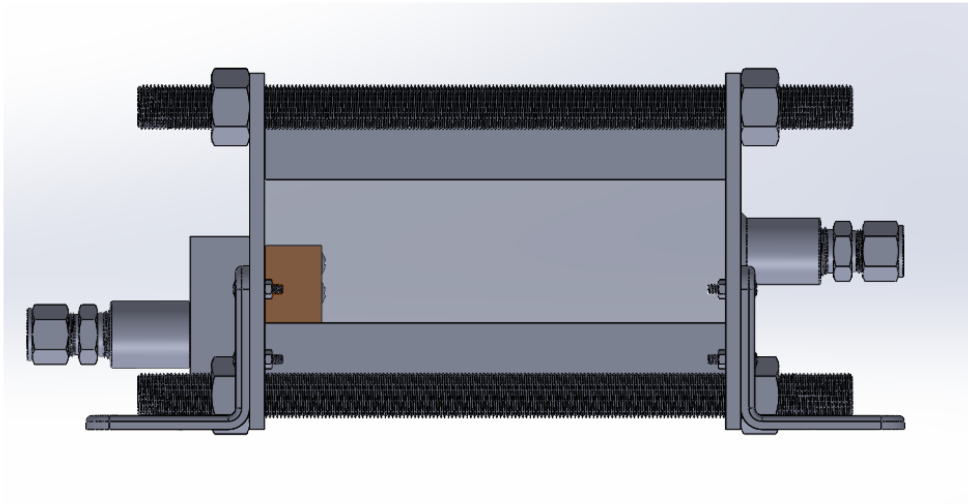


Figure 14: Final Test Rig Design (Front View)

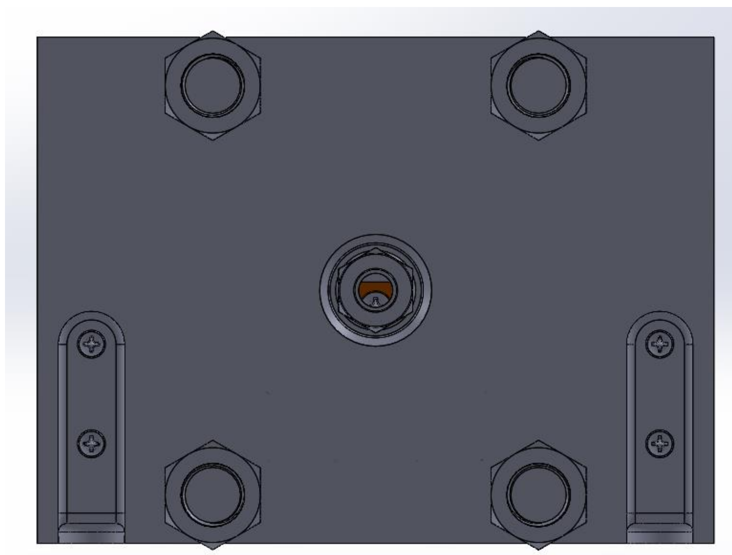


Figure 15: Final Test Rig Design (Side View)

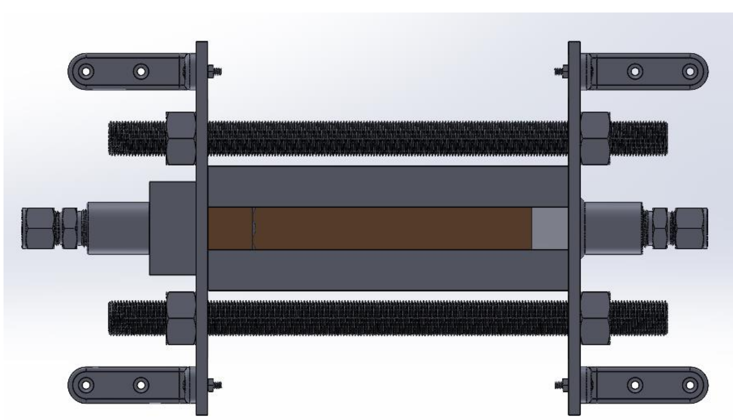


Figure 16: Final Test Rig Design (Top View)

To understand the dimensions and final appearance of the test rig, a drawing detailing some of the important measurements is illustrated in Figure 17. The test rig was created to be portable due to the proposed experimental setup. The compact nature of the test rig allows for quick and easy preparation and clean-up time once the experiment has been completed. The current construction stage of the experimental test rig is visible in Figure 18 while the final appearance is indicated in Figure 19 and Figure 20 contains labels of the key components.

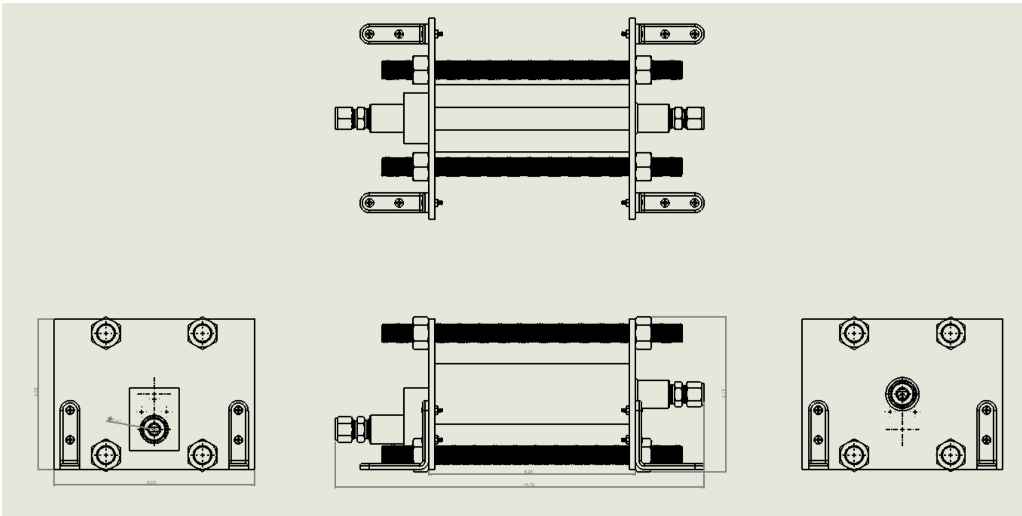


Figure 17: Final Test Rig Drawing

Figure 18: Final Test Rig Construction Process

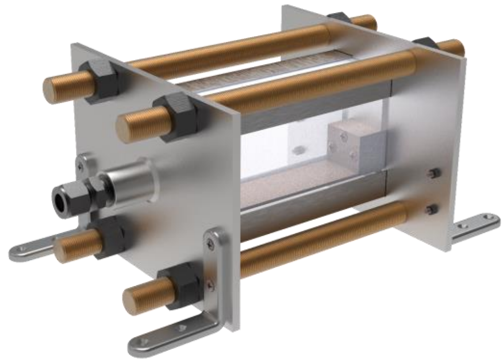


Figure 19: Final Test Rig

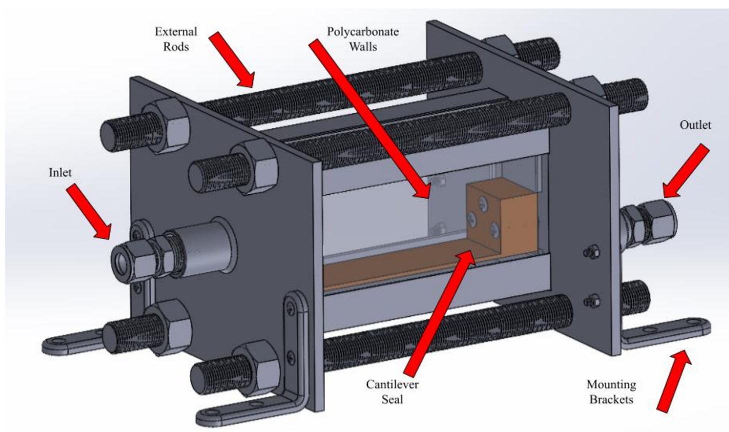


Figure 20: Final Test Rig with Labels

When the test rig is completed, it can be implemented into the proposed experimental setup, atop the F1-10 hydraulic bench. Through this experiment the strain, mass flow rate, and pressure throughout the test rig will be measured. These parameters are important to measure because they affect the performance of the system. The strain of the seal will be measured using a strain gauge, which is useful in determining what its deformation is as the pressure in the test rig creates a distributed load on the seal. The mass flow rate will be recorded with a mass flow meter which will indicate whether there is recirculation within the system and ensures that the storage tank in the F1-10 hydraulic bench has enough space to hold the water flowing through the system. The pressure difference will be recorded by implementing multiple pressure transducers along the length of the flow channel. Pressure transducers are meant to determine the pressure of the water through the system as it flows through the channel. It is evident there is a pressure difference throughout the system due to the direction in which the fluid is flowing and due to the deflection of the plate at the end of the system [17]. Liu and Higgins [18] tested the accuracy of pressure transducers in the field and noted that it is important to keep temperatures within a suitable range because the measured output may be off due to temperature fluctuations. It is important for this constructed system to remain within an acceptable range of temperatures, so the pressure transducers do not provide an incorrect measurement.

Discussion

The experimental test rig has been designed and constructed. In addition to this, the proper instrumentation required for recording the strain, pressure, mass flow rate, etc, is ready to be implemented into the system to begin experimental trials. The numerical results between the simulation and experimental results will not align with one another due to the difference in properties between supercritical carbon dioxide and water, but the same trendline should be expected for experimental trials. For example, the pressure should be at its highest at the inlet of the system and then decrease in pressure as the water flows across the length of the test rig and the seal should deform the most at the free end of the seal, closest to the inlet of the system.

Upon gathering the results, the simulation and experimental results can be compared with one another to ensure that the test rig is working as expected. If there is any discrepancy between the two, the test rig can be analyzed to determine the point of focus and make the necessary adjustments such that the results are comparable.

Future Work

For future simulations it would be beneficial to study the effects of pressure and temperature on viscosity and density. During initial simulations these effects were neglected but could ultimately have an effect on the efficiency and performance of the system. Typically, as the temperature of the fluid increases the density of the fluid decreases which in turn makes the fluid become less viscous [19]. It would also be beneficial to test the system at varying rotor diameters, seal thickness and lengths, and different seal materials. By doing so, the ideal parameters for the seal can be determined and implemented into an experimental design which can be further tested.

The experimental test rig will be tested with three different seals of the same dimensions but made from different materials. As stated, the simulations utilized structural steel for the seal material. For experimental testing this will also be tested along with the inclusion of PEEK plastic and 6061 aluminum alloy. Testing different materials for the seal is important because they have different properties. For this experiment, the modulus of elasticity plays a crucial role in the efficiency and effectiveness of the seal. A material's modulus of elasticity refers to its resistance to elastic deformation, which is the point at which the material is not able to return to its original shape and deformation is permanent [20]. If a seal, or any component of the system, were to suffer from elastic deformation then the efficiency, performance, and life cycle of the system would be reduced. This will require more input into the system and more routine repairs and maintenance, which is sub-optimal. Testing different materials for the experimental setup will aid in this process and show what material, at this scale, is the most practical. Multiple trials for each material will be conducted to ensure that the results obtained are reproducible and reliable for analysis.

Conclusion

This research has demonstrated an understanding of a modern power generation issue and proposes a method of understanding why the seal deforms and can be tested through the utilization of an experimental test rig. allows for thermodynamics and fluid mechanics knowledge to be applied to modern technology and technological advancements. Modern seal technology is not as efficient as it could be due to the high leakage rates, bristle wear, and scalability issues they suffer from, leading to increased cost and energy usage. The methods and results from this research are a solid foundation for future research into analyzing the behavior of seals in supercritical carbon dioxide power generation systems. The experimental test rig allows for the behavior of the seal to be demonstrated on a physical, larger scale, aiding in the visualization of what is happening in existing designs.

References

[1] R. Sun, M. Liu, X. Chen, K. Yang, and J. Yan, “Thermodynamic Optimization on Supercritical Carbon Dioxide Brayton Cycles to Achieve Combined Heat and Power Generation,” Energy Conversion and Management, vol. 251, Jan. 2022.

[2] Muhammad, H. A., Lee, B., Imran, M., Cho, J., Cho, J., Roh, C., Lee, G., Shin, H., Sultan, H., and Baik, Y.-J. (2021). “Investigating Supercritical Carbon Dioxide Power Cycles and the Potential of Improvement of Turbine Leakage Characteristics Via a Barrier Gas.” *Applied Thermal Engineering*, 188, 116601.

[3] Y. H. Fan, G. H. Tang, X. L. Li, and D. L. Yang, “General and Unique Issues at Multiple Scales for Supercritical Carbon Dioxide Power System: A Review on Recent Advances,” Energy Conversion and Management, vol. 268, Sep. 2022.

[4] J. L. C. H. Heshmat, J. Walton, “Technology Readiness of 5th and 6th Generation Compliant Foil Bearing for 10 MWE S-CO_2 Turbomachinery Systems,” no. March, pp. 1-29, 2018.

[5] Bidkar, R. A., Sevincer, E., Wang, J., Thatte, A. M., Mann, A., Peter, M., Musgrove, G., Allison, T., and Moore, J. (2016). “Low-Leakage Shaft End Seals for Utility-Scale Supercritical CO2 Turboexpanders.” *Volume 5A: Heat Transfer*, 139(2).

[6] Ravindranath, B. H., Blythe, N., and Atz, C. (2022). “Systems For A Pump Seal Chamber.”

[7] Tan, M., Lu, Y., Wu, X., Liu, H., and Tian, X. (2021). “Investigation on Performance of a Centrifugal Pump with Multi-Malfunction.” *Journal of Low Frequency Noise, Vibration and Active Control*, 40(2), 740–752.

[8] Luo, Y., Zhang, W., Fan, Y., Han, Y., Li, W., and Acheaw, E. (2021). “Analysis of Vibration Characteristics of Centrifugal Pump Mechanical Seal Under Wear and Damage Degree.” *Shock and Vibration*, 2021, 1–9.

[9] Lyathakula KR, Cesmeci* S, Hassan MF, Xu H, & Tang J. A Proof-of-Concept Study of a Novel Elasto-Hydrodynamic Seal for Supercritical CO2 Turbomachinery Applications. Proceedings of the ASME 2022.

[10] S. Cesmeci, K. R. Lyathakula, M. F. Hassan, S. Liu, H. Xu, and J. Tang, “Analysis of an Elasto-Hydrodynamic Seal by Using the Reynolds Equation,” Applied Sciences, vol. 12, no. 19, p. 9501, 2022.

[11] “F1-10 Hydraulics Bench,” Armfield. [Online]. Available: https://armfield.co.uk/product/f1-10-hydraulics-bench/.

[12] Girdhar, P., and Moniz, O. (2005). *Practical Centrifugal Pumps: Design, Operation and Maintenance*. Newnes

[13] Bachus, L., and Custodio, A. (2006). *Know and Understand Centrifugal Pumps*. Elsevier, Oxford.

[14] Perissinotto, R. M., Monte Verde, W., Biazussi, J. L., Bulgarelli, N. A., Fonseca, W. D., Castro, M. S., Franklin, E. de, and Bannwart, A. C. (2021). "Flow Visualization in Centrifugal Pumps: A Review of Methods and Experimental Studies." *Journal of Petroleum Science and Engineering*, 203.

[15] Basse, N. T. (2017). "Turbulence Intensity and the Friction Factor for Smooth-and Rough-Wall Pipe Flow." *Fluids*, 2(2).

[16] Almasi, A. (2015). "Make The Most of Centrifugal Pumps." *Make the Most of Centrifugal Pumps*, 77(7), 29–32.

[17] Hafizi, Z. M., Vorathin, E., Aizuddin, A. M., and Lim, K. S. (2019). "High-Resolution Fibre Bragg Grating (FBG) Pressure Transducer for Low-Pressure Detection." *International Journal of Automotive and Mechanical Engineering*, 16(2), 6783–6795.

[18] Liu, Z., and Higgins, C. W. (2015). "Does Temperature Affect the Accuracy of Vented Pressure Transducers in Fine-Scale Water Level Measurement?" *Geoscientific Instrumentation, Methods and Data Systems*, 4(1), 65–73.

[19] K. S. Lee, "Hybrid Thermal Recovery Using Low-Salinity and Smart Waterflood," in Hybrid Enhanced Oil Recovery using Smart Waterflooding, J. H. Lee, Ed. Elsevier Inc., 2019, pp. 129–135.

[20] D. R. H. Jones and M. F. Ashby, "Elastic Moduli," in Engineering Materials 1: An Introduction to Properties, Applications and Design, 5th ed., Elsevier Ltd., 2019, pp. 31-47.