Injector Design for an Oxy-Fuel sCO2 Cycle Combustor and Specification of components for a Liquid Hydrogen Test Facility

University Turbine Systems Research (UTSR)

2017 Gas Turbine Industrial Fellowship Program

Prepared by: Timothy Cook

M.S. Candidate, Aerospace Engineering

Georgia Institute of Technology, Atlanta, GA

Prepared for: David Ransom

Manager, Propulsion Machinery, Division 18

Southwest Research Institute, San Antonio, Texas

And

Timothy Allison

Manager, Rotating Machinery Dynamics, Division 18

Southwest Research Institute, San Antonio, Texas

1. Introduction

As an independent research organization, Southwest Research Institute serves a diverse clientele with a background in numerous industries. The Mechanical Engineering Department, Division 18, is just one branch of the institute working on a broad range of applications, from Power systems to Manufacturing. SwRI is a leader in supercritical carbon dioxide power cycle research, operating the largest sCO_2 cycle test loop in the world and division 18 is developing the technology necessary for a production sCO_2 Power system, including turbine and combustion development.

This fellowship split tasks between the Fluid Machinery and Rotating Machinery sections under Division 18. The primary accomplishment during the fellowship was the preliminary design of injectors and viewing windows for the oxy-fuel direct-fired sCO_2 combustor. In addition, this fellowship contributed to system design for a new liquid hydrogen test facility for hydrogen flow component testing, along with planning considerations for future installations of bulk energetic material storage.

2. Oxy-Fuel sCO_2 Combustor

2.1. Background

The supercritical carbon dioxide Brayton power cycle is similar to Brayton and Rankine power cycles commonly employed for power generation, using air and water, respectively, as their working fluids. Supercritical CO_2 as a working fluid provides a number of advantages over these other cycles because of its density, specific heat and supercritical phase properties. Studies have shown that the theoretical efficiencies of sCO2 Brayton cycles, particularly the recuperated recompression CO_2 Brayton Cycle (RCBC), are much greater than traditional Rankine cycles, as quantified in Figure 1 below. The flow components for a sCO_2 cycle are approximately ten times smaller than that of a similar Rankine cycle, reducing the capital cost and footprint of sCO2 cycle generation systems (Brun *et al.*, 2017).

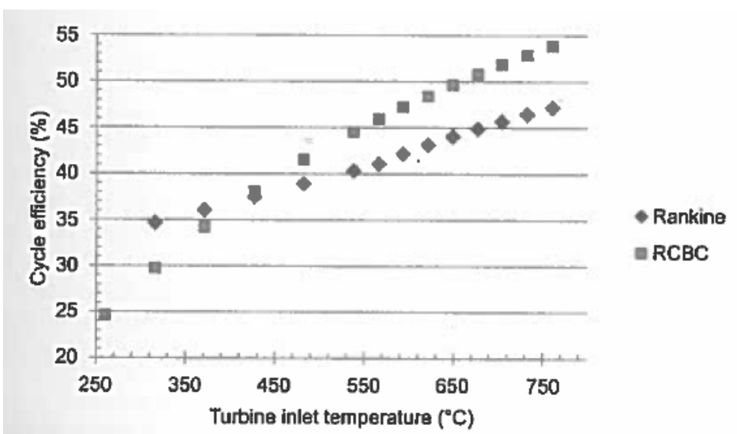

Figure 1 Comparison of Recuperated sCO_2 Brayton cycle efficiency to Rankine cycle, with varying turbine inlet temp

A direct-fire oxy-fuel sCO_2 cycle is a semi-closed cycle for which the primary heat source is a combustor, burning a gaseous fuel and concentrated oxygen within the medium of inert CO_2. Figure 2 depicts the process diagram of a simple, recuperated direct-fire sCO_2 cycle. A practical oxy-fuel cycle would concentrate oxygen from ambient air for combustion. After the turbine, water and other combustion byproducts are separated out.

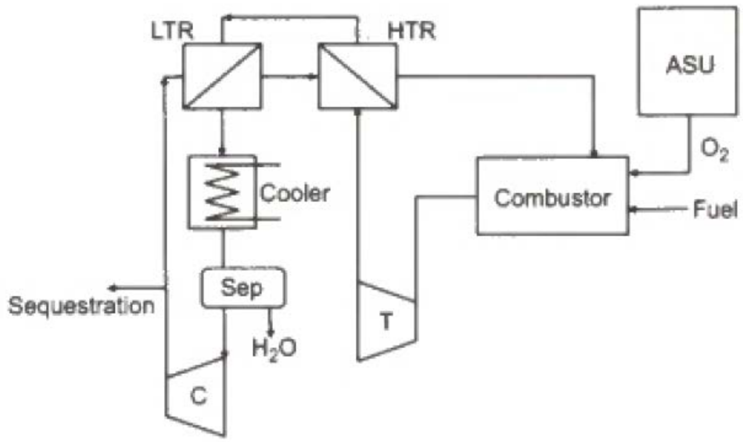

Figure 2 Process Diagram for a recuperated direct-fire sCO_2 Brayton cycle with direct CO_2 sequestration post-compressor

Direct fire provides for higher turbine inlet temperatures and direct sequestration of the carbon byproducts, making this cycle particularly attractive in expectation of future restrictions on greenhouse gas emissions. However, many technological challenges remain to building a practical direct fire sCO_2 Brayton cycle power plant. Chemical kinetics at pressures in excess of 20MPa and in high concentrations of CO_2 have been poorly studied, while turbines and seals to withstand the conditions and chemical properties of the impure mixture have yet to be developed. SwRI is a leader in research on direct-fire sCO_2 cycles, with a number of projects dedicated to solving these challenges.

2.2. Injector Design

Southwest Research is in the development phase of a MW-scale oxy-fuel sCO2 combustor for demonstration and research. Development of a combustor model for numerical simulation required an injector for the inlet of oxygen, methane and carbon dioxide into the combustor. One of the main goals of the fellowship was to design such an injector to suit the requirements of the combustion system. This entailed research on injector design, creation of a solid model and preliminary numerical simulation to verify flow properties.

2.2.1. Literature Review

As no injector design guidelines exists for oxy-fuel combustion in sCO_2, a review of other current injector designs was necessary at the outset. The proposed combustor was a swirl stabilized, non-premixed configuration, similar to gas turbine engines using gaseous fuels. The literature review, therefore, focused on gas turbine injector design and swirl stabilization to identify criteria for the injector design.

Swirl Stabilized combustors rely on a central recirculation zone to anchor the flame in the combustor and prevent blowout. The tangential velocity of the swirling jet causes divergence, eventually leading to vortex breakdown and the development of a toroidal recirculation zone. As the intensity of the swirl is increased, the recirculation zone remains narrow and extends further downstream, but eventually becomes broader and shorter at high swirl intensities (Gupta *et al.*, 1984).

The Swirl Number is a measurement of the swirl intensity, defined as a ratio of the axial flux of tangential momentum to axial momentum within the jet. Vortex Breakdown first occurs at swirl numbers of 0.3-0.6 (Gupta *et al.*, 1984; Al-abdeli & Masri, 2003). Flame stability is greatest (characterized as its resistance to blowout) over a broad range of equivalence ratios in a moderately swirled jet. For this reason, most practical applications of swirl injectors seem to utilize a swirl number of .6-1.5 (Dombard *et al.*, 2012), where a long, narrow recirculation zone is expected.

While numerous devices exist for imparting swirl, an annular vane mechanism is arguably the simplest design. The swirl number of an axial vane swirler is not a function of jet velocity and can be approximated from swirler dimensions alone by:

$$S = \frac{2}{3}\frac{[1-(d_h/d)^3]}{[1-(d_h/d)^2]}tan\phi$$

Where d is the diameter of the swirler nozzle, d_h is the diameter of the central hub of the vanes and ϕ is the vane angle at the outer diameter. Axial swirlers are not efficient above a swirl number of one, due to flow obstruction by the fan blades, but pressure drop was not a major concern for the application (Gupta *et al.*, 1984).

2.2.2. Design

The injector delivers a swirled, dilute mixture of oxygen in carbon dioxide to the combustion chamber with a central fuel jet of methane. The simplicity of the annular vane design allowed for a quick calculation of dimensions for varying mass flow rate, velocity and swirl intensity. Multiple models were then produced with different dimensions. Injection velocities were given between 25-50 m/s for the O_2/CO_2 mixture. Target swirl number of 1.0 was chosen based on an initial comparison to a 0.6 swirl number. The swirler vanes were straight vanes with a varying angle from hub to tip.

2.2.3. Numerical Simulation

In order to produce stable combustion, a swirl injector should produce a central recirculation zone within the jet. Various factors lead to the idealized swirl injector model out-performing the real model. With this consideration, The injector models were tested using CFD simulation in ANSYS Fluent to verify the desired flow properties.

Implementation of the simulation, in itself, is a skillful task. Inlet, outlet, boundary conditions and solution settings must be correctly chosen to yield a useful result. Initial simulations using the steady state Reynolds-averaged Navier-Stokes solution would not converge. By analysis of the developing computation, it was determined that the vortex produced downstream exhibited precession about the chamber axis. This violates the steady state assumption of the RANS solver and requires a transient analysis to properly converge on a solution.

The successful transient analysis revealed a strong recirculation zone between one and two jet diameters downstream of the high swirl nozzles. Injector designs with higher velocity and lower swirl numbers did not produce a strong central recirculation. One explanation for this could be the narrow confinement of the chamber, which forms strong exterior recirculation and impedes expansion of the swirling jet.

Figure 4 is an instantaneous axial velocity contour on the cross-section down the axis of the chamber. The flow is biased toward one half of the chamber, forming a lopsided toroidal recirculation zone which rotates about the central axis. Figure 5 further shows the velocity vectors through the chamber, by which the flow reversal can easily be observed.

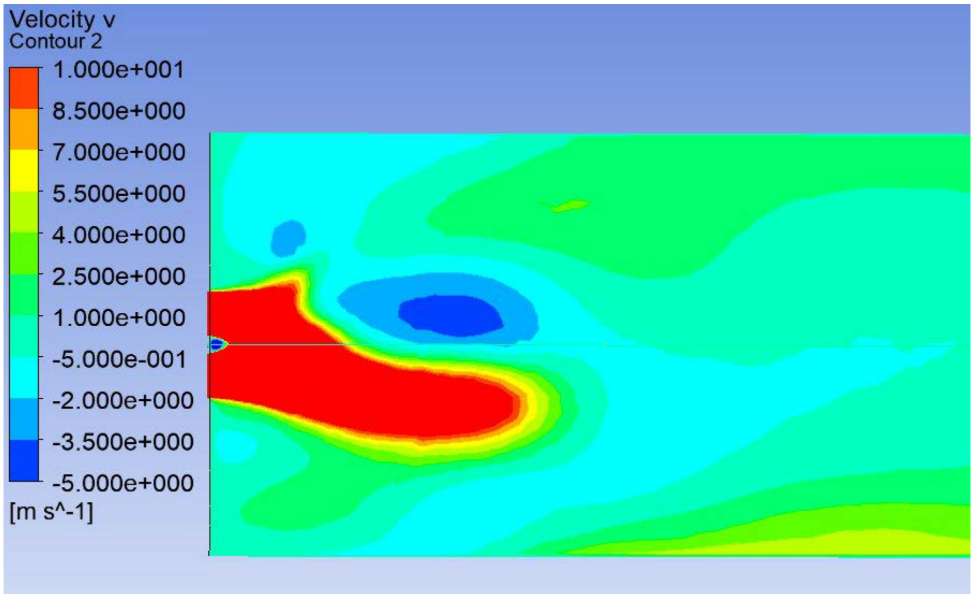

Figure 3 In-chamber axial velocity contour on x-y plane showing negative velocities indicating recirculation

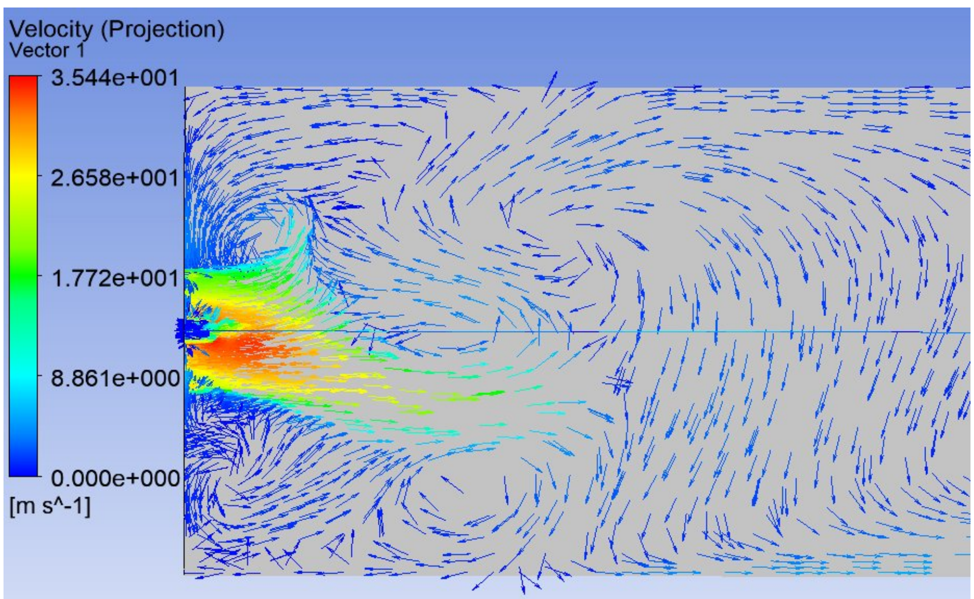

Figure 4 Vector plot on x-y plane showing vortices of recirculation zone. Note strong bias of the jet toward the bottom of chamber, suggesting the vortex core is unstable or transient

Further work remains in order to produce a robust injector design for future combustor development. The work done during this fellowship produced a starting point for this injector design, with a basic geometry and framework for CFD simulation. No analysis was conducted with fuel injection through the central orifice. Consequently reactant mixing and fuel distribution was not considered, which will be a major driver of future development.

2.3. Window Design

Optical diagnostics of combustion at the proposed pressures and high concentrations of CO_2 do not currently exist in the literature. An objective of the proposed combustor is to provide optical access to the flame for analysis by a variety of techniques. Such methods as PIV, chemiluminescence and shadowgraphy require access from multiple angles to allow light to pass in and out of the combustor. It is, therefore, necessary to design a system of windows, providing perspectives perpendicular to the axis of the combustor, at 0, 90˚ and 180˚ ('front', 'top' and 'back').

2.3.1. Design

The cylindrical combustor contsists of three layers, which all must be transparent to obtain optical access to combustion. The outer pressure container had already incorporated a sight glass rated for the temperature and pressure differential at the outer case. The inner liners facilitate flow separation and mixing, with the inner cylinder containing the combustion flow and the outer containing the cooling and dilution flows. The pressure differential over these windows is expected to be mainly due to pressure fluctuations. As such, thinner windows can be used for these liners.

A full cylindrical transparent section was proposed for the inner liner to reduce the intrusion of window settings into the combustion flow path. This design also provides the greatest viewable area within the combustor. The outer liner window was designed to be flat, as intrusions into the cooling flow path is less of a concern.

The window material must possess suitable physical and optical properties. Combustion temperatures up to 1900˚C are expected within the inner liner, requiring a material with high melting point and resistance to thermal gradients. The window material should also transmit light in the mid-wave infrared spectrum for specific optical diagnostics. Sapphire is an excellent choice for these criteria, with a melting point above 2000˚C, softening point at 1800˚C, and transmission over 70% at 4000 nm wavelength through a ¼" pane thickness. Electrically fused quartz is 10-25% of the cost of Sapphire, but its lower softening point, at 1700˚C, and transmissivity around 30% at 4000nm would make it much more difficult to use.

Preliminary window design, sizing (based on proposed camera specifications), CAD models and stress analysis were accomplished during the fellowship, as well as cost analysis and material availability.

3. LH_2 Facility System

3.1. Background

The final major contribution of this fellowship is the design work for a new liquid hydrogen component testing facility at SwRI. The purpose of this facility is to test components of a liquid hydrogen transfer system. Planning included not only specification of the system components, but also data acquisition, power requirements, and fire and safety code considerations.

3.2. Design

A large bulk tank would supply LH_2 to a configuration of smaller tanks and other components for testing. Testing plans require targeted flowrates through certain components in the system, with helium and hydrogen gases pressurizing parts of the system. Limited control of pressure within the supply tank and the absence of a mechanical pump necessitates proper sizing of LH_2 piping, valves, gas tubing, vaporizers and venting stacks. Vacuum jacketing and composite aerogel insulation for various components of the system is also a requirement to reduce boil-off. Figure 6 is the piping and instrumentation diagram, detailing most of the flow system for the facility.

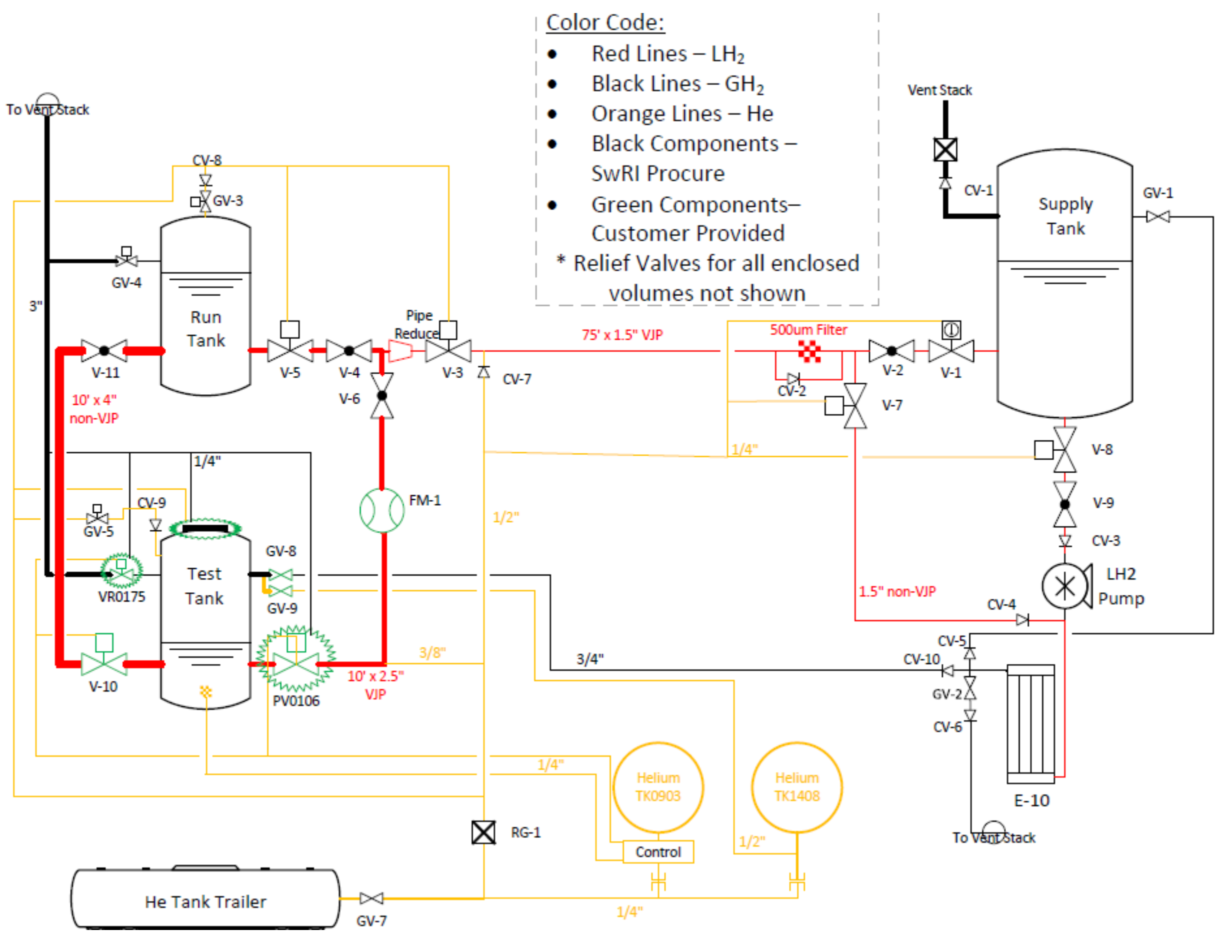

Figure 5 P&ID of liquid hydrogen test facility with supply/vaporizer (right), Helium system (bottom), and test section (left).

A significant portion of this work involved interpretation and compilation of fire and safety codes to ensure compliance of the new facility. The City of San Antonio and the federal government require compliance with multiple codes, including the International Fire Code (IFC), National Fire Protection Code (NFPA) and the Occupational Safety and Health Act (OSHA). These codes dictate materials, locations and protection systems that must be incorporated to complete the permitting process.

A major component of the fire and safety regulations are stand-off distances between hazardous storage tanks and exposures. As an extension, additional research was done to help plan future installments of natural gas, oxygen and carbon monoxide tanks in the vicinity of the original project.

4. Acknowledgements

I would like to thank Southwest Research for choosing me for the UTSR Fellowship and investing in my education. I am very grateful for my introduction to the supercritical oxy-fuel system. As I transition back into industry after school I will definitely be considering this field. Throughout the fellowship, I felt like a valued member of the team and had the support of the entire group. I would especially like to extend my gratitude to Klaus Brun, David Ransom and Tim Allison for integrating me into their teams. Also to Jacob Delimont, C.J. Nolan, Nathan Andrews, Shane Coogan, Griffin Beck, Ryan Cater and Dorothea Martinez for providing meaningful tasks, mentorship, and patience.

5. References

Brun K., Friedman, P. & Dennis, R. (2017) *Fundamentals and Applications of Supercritical Carbon Dioxide (SCO2) Based Power Cycles*. Woodhead Publishing

Al-Abdeli, Y. M. & Masri A. R. (2003) *Stability characteristics and flowfields of turbulent non-premixed swirling flames*. Combustion Theory and Modelling, 7 (2003), 731-766

Gupta, A. K., Lilley, D. G. & Syred, N. (1984) *Swirl flows*. Abacus Press.

Dombard, J., Poinsot, T., Moureau, V., Savary, N., Staffelbach, G., & Bodoc, V. (2012) *Experimental and numerical study of the influence of small geometrical modifications on the dynamics of swirling flows*. Center for Turbulence Research Proceedings of the Summer Program 2012.