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Development of a Laser Igniter for Direct Fired sCO2 Combustors

Sreenath Gupta, Shashikant Aithal
Argonne National Laboratory
Lemont, IL 60439

Ashvin Hosangadi, Tim Weathers
CRAFT-Tech Inc.
Pipersville, PA 18947

Jeremy Fetvedt
8Rivers Capital
Durham, NC 27701

1.0 INTRODUCTION

Allam-Fetvedt cycle power plants offer almost zero emissions and cost of energy that is on par with traditional Rankine cycles while using traditional fossil fuels like coal and natural gas. At this point of time, several organizations are engaged in the development of the required hardware components for Allam-Fetvedt cycle power plants. Previous cycle optimization efforts have identified the combustor to operate at 300 bar pressure while providing a combustor exit (i.e., turbine inlet) temperature of 1150ºC. Moreover, the oxy-fuel combustion occurs under heavy dilution with CO_2 concentrations (up to 90%). Under such adverse conditions, ignition remains a challenge.

Governed by Paschen's law and limited by dielectric strength of materials, electrical spark ignition is limited for use under fairly low pressures (< 30 bar). Similar to what is used in aviation gas turbines, Mitsubishi [1] has used a spark plug with extended electrodes and used a mechanism to retract the spark plug after successful ignition. Though this avoids perturbation of the combustor flow field by the ignition hardware, the ignitable pressures still remain fairly low (~ 24 bar). Use of hypergolic chemicals to ignite the mixtures, as currently performed in rocket combustors, is a possibility. However, these chemicals tend to be highly toxic and are difficult to handle.

Recently after evaluating several options for ignition, SwRI [2] had identified laser ignition to be an ideal candidate: In this mode of ignition, a pulsed laser is focused into a narrow volume where the photon-molecule interaction probability increases with pressure. In other words, it becomes easier to ignite the combustible mixtures at higher pressures by using laser ignition.

The authors previously have developed and demonstrated laser igniters on a 6-cylinder QSK19G natural gas reciprocating engine [3]. That effort highlighted the ability to significantly improve ignition probability through spatial and temporal distribution of the ignition kernels by laser ignition. Also, it was found to enable the use of higher dilution levels. Through appropriate design features, it was even possible to keep the igniter optics sufficiently clean to enable engine operation up to 6000 hrs. [4].

In this work, we describe our effort to adapt our laser igniter for Allam-Fetvedt cycle combustors where pressures could be as high as 300 bar under combustion temperatures. To be on par with typical gas turbine igniters, a life expectancy of 5000 ignitions was chosen as the target.

2.0 CFD Simulations

For a sCO2 combustor at an elevated pressure, four parameters play an important role in the successful transition of plasma kernel into a flame: temperature, velocity, local equivalence ratio, and CO_2 concentrations. To determine the distribution fields of these parameters, a high-fidelity large-scale CFD simulation was performed. Previous CFD effort performed in a 5MWTh sCO_2 combustor [5], and the more recent effort by Zambon [6] were used for guidance.

2.1 Geometry: The sCO2 combustor geometry was provided by 8Rivers and is described in detail in reference [7]. The arrangement is similar to that of a typical gas turbine combustor (see Figure 1) where the fuel is introduced through a nozzle at the center and a co-flowing oxidizer stream is introduced concentrically using a swirler. Both the oxidizer and the fuel streams have CO_2 added as a diluent to significantly reduce the combustion temperature. Additionally, CO_2 as a diluent is introduced along the length of the liner to keep it cool, and radially inward in the secondary and tertiary combustion zones to limit the combustor exit temperatures, i.e., turbine inlet temperatures to 1150°C.

Using 1/6 symmetry of the combustor geometry, a hybrid mesh was created using Pointwise: Interior volume mesh created using Pointwise®'s new voxel solver which inserts axis aligned hexagonal cells for better flow aligned cells improving solution quality. The computational grid for 300 bar model consisted of 4.2 million cells. Similar grid for 20 bar simulation consisted of 5.4 million cells. These mesh structures allowed capturing the nuances introduced by the CO_2 diluent/ coolant streams on the combustor flow field.

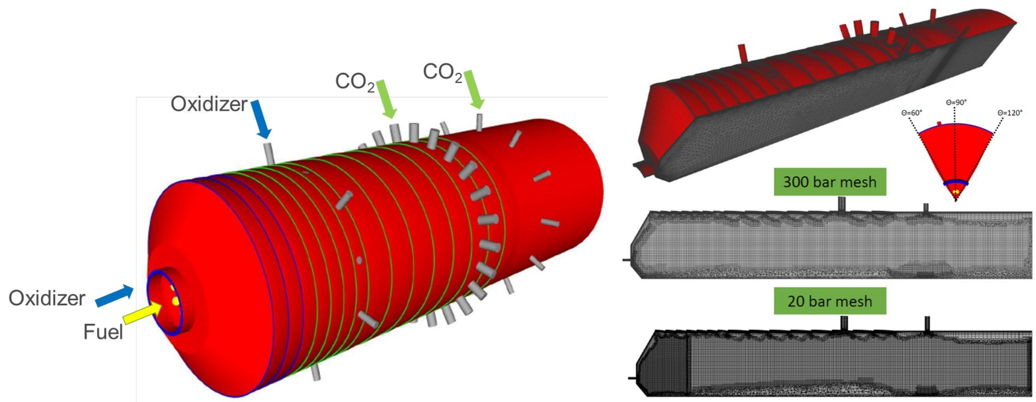

Figure 1: *(left)The combustor geometry; (right) The mesh generated using 1/6 geometry.*

2.2 Setup: While using the CRUNCH CFD® unstructured solver, steady state simulations were performed for the 50 MWth geometry for a chamber pressure of 20 bar and 300 bar for a non-reacting system (cold flow). The Soave-Redlich-Kwong (SRK) Equation of State (EOS), and k-ε turbulence model with wall functions were used for the simulations using an Implicit Gauss-Seidel flow solver. The H_2, CO_2, and O_2 mixtures were modeled using the SRK-EOS while CO was modeled as a thermally imperfect gas. All simulations were conducted on Broadwell nodes (Intel Xeon E5-2695v4) on Bebop which is a 1 pF mid-range supercomputing cluster at Argonne National Laboratory.

2.3 Fuel and Oxidizer compositions: The simulations were carried out using a coal derived syngas (mole fractions $CO_2 = 0.139$, $CO = 0.608$, $H_2 = 0.253$) and an oxidizer (mole fractions $O_2 = 0.235$, $CO_2 = 0.765$). The flow rates and temperatures of the inflowing gas streams were determined as the outputs from an ASPEN Hysis model that simulated the Allam-Fetvedt cycle.

2.4 Test Matrix: CFD modeling of steady state flow fields prior to ignition was performed at 20 bar which was representative of conditions during plant startup, and at 300 bar which was representative of the combustor full load conditions. The steady state flow field at 20 bar (see Figure 2), exhibited multiple recirculation zones. The associated fields for CO_2, O_2, temperature and velocity were also determined.

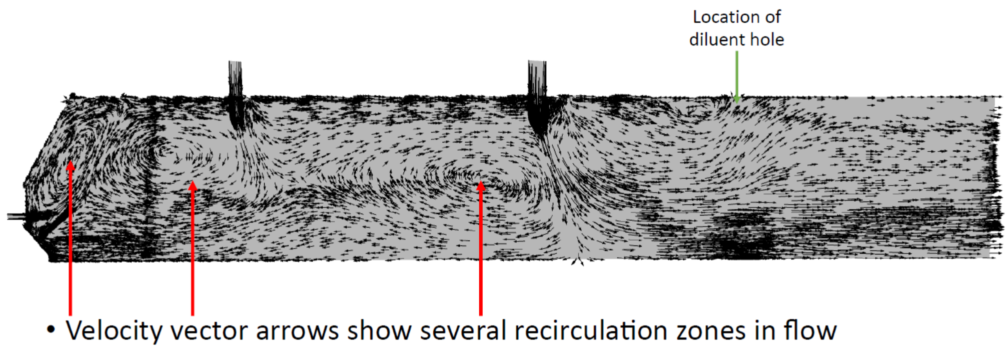

Figure 2: *20 bar flow field. Cutting plane θ=75°*

The iso-volumes for equivalence ratio, in the range of 0.95 and 1.05 are shown in Figure 3. Closer to the fuel nozzle, these iso-volumes expand out like flower petals. Both the fields shown in Figure 2 *and* Figure 3 allow one to avoid regions with velocities greater than 30 m/s, or with equivalence ratios too rich or too lean to result in quenching of the flame kernel. After a thorough investigation it was decided to place the igniter through a radial penetration in the combustor casing, either in the 2nd or the 3rd rung of the liner. Also, the ideal placement of the ignition kernels was identified to be radially inside the petals. Similar conclusions were drawn for simulations performed at 300 bar.

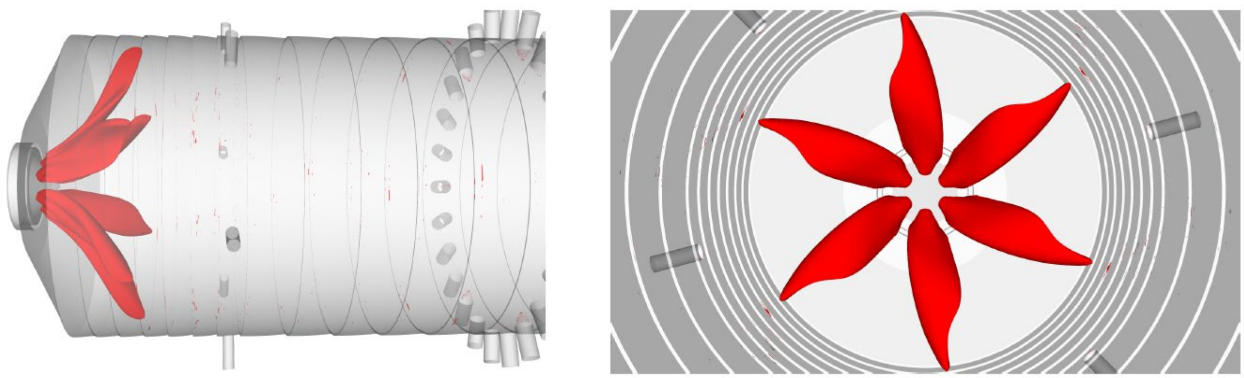

Figure 3: *Iso-volumes of ϕ = 0.95 – 1.05 for the 20 bar case*

For an igniter placed on the casing in a radial direction, the pressure retaining window/lens can at best be placed somewhere between the liner and the casing inner wall. This requires the focusing optic to have a focal length between 50 mm and 165 mm.

3.0 Igniter Development and Evaluation

3.1 Laser Igniter

The laser igniter design was fine-tuned through several iterations of the optical, mechanical and thermal designs. The design features of the laser igniter and its operational characteristics are given in Figure 4. A high-power pulsed laser was used to accommodate focusing and creating a spark at distances up to 165 mm (from the outer diameter of the combustor vessel). Also, the igniter incorporated an outer tube affixed to the combustor casing, and an inner tube attached to the front of the laser. The distal end of the outer tube carried a sapphire lens with appropriate sealing arrangement. A telescopic arrangement between the outer tube and inner tube allowed alignment of the laser beam with the sapphire lens, and further allowed easy installation on the combustor.

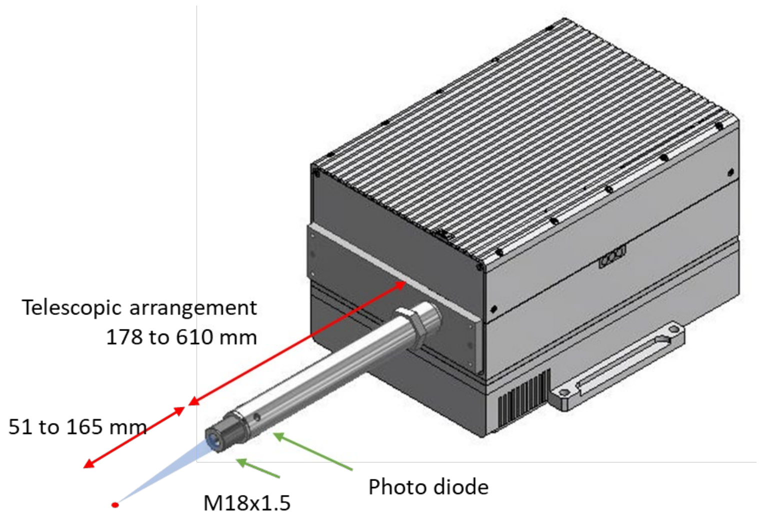

Figure 4: *sCO2 combustor Laser Igniter*

3.2 Igniter Performance Evaluation

The laser igniter was tested in a static chamber at room temperature prefilled with premixed gaseous mixtures of syngas and oxidizer. The igniter proved successful over a wide range of equivalence ratios, $\phi = 0.7$ to 1.6, and for initial pressures up to 40 bar (see Figure 5). These tests also showed that multiple ignition kernels form at the focal point along the laser line of sight roughly spread over 25 mm (see Figure 6). This volumetric ignition along with the use of multiple ignition pulses (i.e., burst mode) significantly improve ignitability.

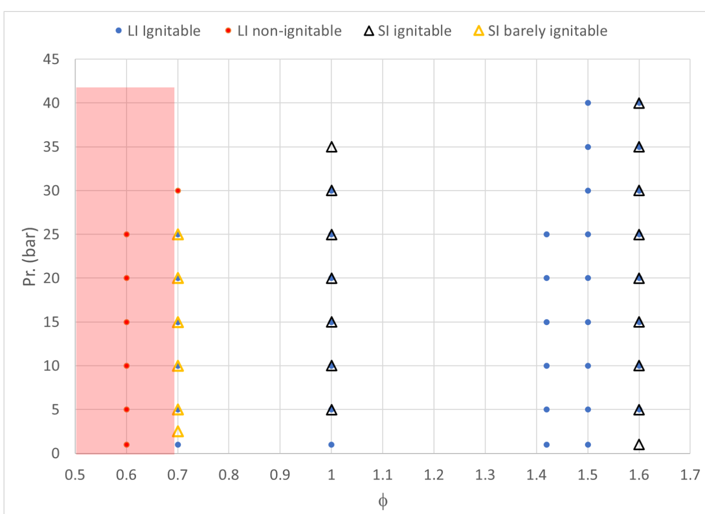

Figure 5: *The ignitability map of the coal derived syngas-oxidizer mixtures. Focal length = 150 mm.*

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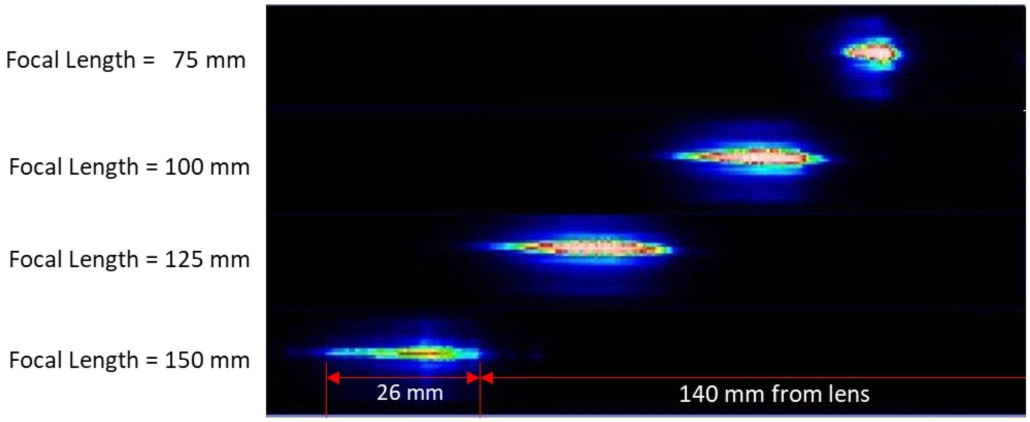

Figure 6: *Laser initiated plasma kernel images in compressed Air @ 2000 psi (ρ=164 kg/m3); Composite image of 20 shots, exposure time = 1μs. The Laser propagation is from right to left.*

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