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laser Igniters for Direct-Fired Supercritical CO_2 Combustors

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Abstract: Allam-Fetvedt cycles, which use supercritical CO_2 (sCO_2) as the working fluid, enable power generation with no pollutant discharges while using traditional fossil fuels. In this paper we present our efforts to develop a laser igniter that overcomes the ignition challenges due to high CO_2 concentrations and high-pressures in the sCO_2 combustor. Flow field simulations were performed to identify optimal locations for the placement of the ignition kernels using the commercial code, CRUNCH-CFD. Based on the simulations results, a laser igniter was designed and subsequently tested for performance in a static chamber. Tests in compressed air showed ignition kernel locations to be repeatable over a wide range of pressures. For tests performed in pure carbon dioxide, owing to its non-linear optical behavior, the ignition locations were found to vary with pressure. However, based on observations in tests using fuel-oxidizer mixtures, the optical nonlinearity of carbon dioxide is projected to have a relatively small effect on ignition in typical sCO_2 combustors.

1. INTRODUCTION

While using traditional fossil fuels like coal and natural gas, the Allam-Fetvedt supercritical CO_2 cycle power plants offer (i) very high efficiencies, (ii) no pollutant discharges, (iii) dry-cooling, (iv) the possibility of carbon sequestration, (v) smaller system hardware, and (vi) cost of energy that is on par with traditional Rankine cycles [1]. Ignition remains a concern in the combustors of these power plants due to three reasons:

(i) Combustors operate under very high pressure (~300 bar),

(ii) Combustors operate under high dilution levels by CO_2 (up to 90% by vol.)

(iii) Currently, these combustors are ignited at low pressures (~24 bar) and the operating pressure is slowly increased. In case of a flame blow-off, the time required to spool down, reignite, and spool up to the operating pressure could take several hours.

Laser ignition offers (i) easier ignition at higher pressures, (ii) ignitability over a wider range of equivalence ratios (ϕ) and dilution levels, and (iii) ignition hardware that remains remotely located and avoids perturbation of the flow field. As a result, we focused on developing a laser igniter specifically for sCO_2 combustors.

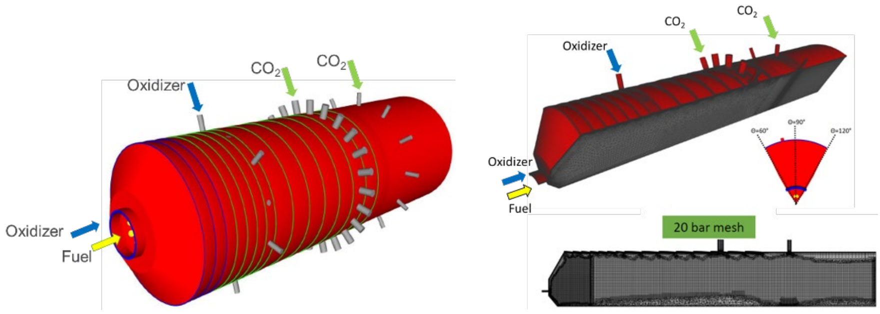
In the past 20 years, spurred by the potential of fuel savings and reduced NO_x concentrations in reciprocating engine exhausts, several research groups, including the Argonne group, have developed low-power, compact and rugged laser igniters. Notable among those are the efforts by Taira et al. [2], Pavel et al. [3], Gerhard Kroupa et al. [4]. The authors, as a part of the Argonne group, developed a laser igniter using a VCSEL pumped Nd:YAG laser with passive Q-switching. Tests performed in a 350 kW, 6-cylinder, stationary natural gas engine showed efficiency improvements of 2.6% points while meeting EPA mandated NO_x concentration levels [5]. In all of these efforts, the beam emanating from a Nd:YAG or Nd:YLF laser is focused into the gas medium to result in a plasma kernel due to gas breakdown. This mode of ignition, often called laser induced breakdown ignition (LBI), requires high laser energies but offers the flexibility of placing the plasma kernel at the optimal location in the flow field. The alternative, Laser Ablative Ignition (LAI), creates the plasma kernel by focusing the laser pulse on a solid target like a metal surface. LAI requires 40 times smaller laser energies but the requirement for laser incidence on to a solid surface becomes too restrictive in designing the igniter. As a result, the effort reported here was limited to designing a laser igniter while using LBI.

The use of laser ignition for sCO2 applications is in its incipient stages. Katcher et al. [6] reviewed several methods of ignition in sCO2 combustors to favorably rank laser ignition. Later, the SwRI group [7] demonstrated laser ignition in a small model combustor. Shinju Suzuki et al. of Toshiba [8] demonstrated laser ignition on a 50 MW combustor. However, the details of their igniter have not been shared in detail, and it appears to be more like a lab-scale setup. In this paper, we have performed a 3D-CFD flow field modeling on one 50 MW sCO2 combustor design to obtain the operational parameters for the igniter. For the laser igniter so designed, the effect of optical non-linearity of CO2 under typical sCO2 combustor conditions is investigated. Also, the effect of property variation near the Widom line in the supercritical region is investigated.

2. CFD MODELING OF A 50 MW COMBUSTOR

As sCO_2 technology is rather new, not much is known about the operating envelope or the design parameters for the igniter. To estimate these values, 3D-CFD simulations of the flow fields prior to the ignition event within a 50MW combustor were performed using the commercial code CRUNCH-CFD from CRAFT Tech. The design of the prototype combustor was provided by 8Rivers [9]. Estimates of the fuel, oxidizer, and diluent flow rates and temperatures were obtained by a 1-D model developed in ASPEN Plus simulating the Allam-Fetvedt cycle. Two sets of simulations were performed: one at 20 bar simulating pre-ignition conditions, and other at 300 bar simulating full load conditions. While most of the simulation details are provided in reference [9], the important findings of that effort are replicated below.

A schematic of the 8Rivers' sCO_2 combustor is shown schematically in Figure 1a. It closely mimics a typical gas turbine can combustor with coal-derived syngas fuel injected at one end. The oxidizer is introduced concentrically using a swirler, and from the edges of the first three rungs. Carbon dioxide from the cycle is introduced in the first and second set of dilution holes and from the edges of the rest of the rungs. The full combustor geometry has a 1/6 symmetry (based on the 6 oxidizer inlets). This symmetry in the combustor geometry was exploited in the CFD simulations to reduce the computational resources required for the simulations. An adaptive mesh with 5 million cells was generated to perform CFD simulations on this 1/6 geometry (see Figure 1b).



(a) (b)

Figure 1 (a) Schematic representation of the sCO2 combustor, (b) 1/6 geometry used for CFD simulations.

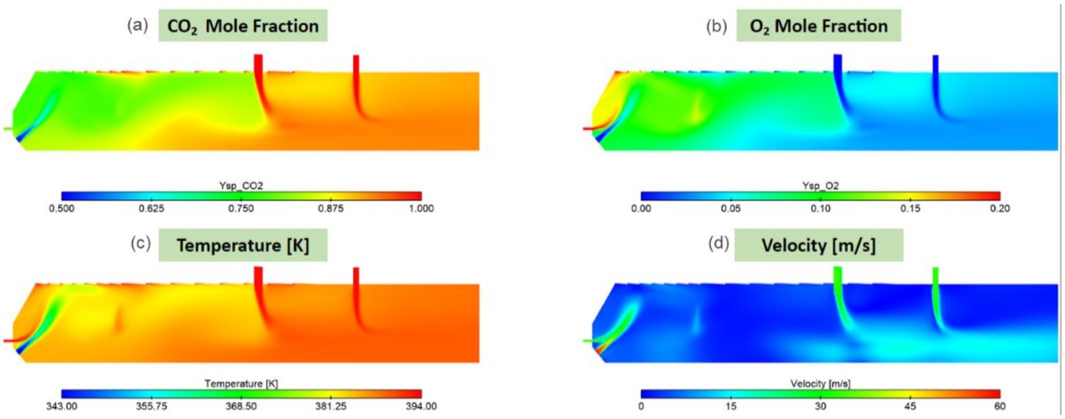


Figure 2 Flow filed distributions at 20 bar combustor conditions.

CFD simulations yielded distributions of CO_2, O_2, velocity, and temperature (see Figure 2 (a)-(d)) in addition to a distribution of the local equivalence ratio. Figure 2 (a) shows the mass fraction of CO_2 in the combustor. The longitudinal injection of CO_2 downstream of the main fuel and oxidizer injection near the inlet leads to the mixing of the fuel/oxidizer and diluent streams. Due to the addition of the CO_2 diluent via two inlets, the right half of the combustor has very high levels of CO_2. Figure 2 (b) shows the mass fraction of O_2 in the combustor. Here it is seen that the mass fraction of O_2 to be considerably high near the left half of the combustor. Figure 2 (c) shows the temperature field. The inlet temperatures of the fuel, oxidizer and CO_2 can be seen in this figure. The mixing of the fuel, oxidizer and diluent streams can be seen. Figure 2 (d) shows the velocity field in the combustor. Near the left half of the combustor there are large regions where the flow velocity is between 0 and 15 m/s. For a given pressure of the combustor, higher local temperatures enhance ignition, whereas higher velocities tend to quench the ensuing flame front. Also, the ignition plasma kernel needs to be placed where the local fuel-oxidizer mixture is within the ignition limits for successful ignition to take place, i.e., the incident plasma kernel to transform into a self-sustaining flame front.

The simulated flow fields were carefully evaluated for optimal placement of the ignition kernel that ensures ignition. The criteria used was velocity < 30 m/s and $\phi = 1.0 \pm 0.05$. Subsequently, it was decided to install the igniter perpendicular to the combustor axis and the igniter port on the 2nd rung of the combustor since this is the region which has high O_2 mass fraction as discussed above and also has relatively low flow velocities. For a potential installation of the converging optic on the inner walls of the casing, radial profiles of the flow fields showed that the ideal focal lengths for the converging optic were between 51 and 165 mm.

Also, it became apparent through the CFD analysis that the temperature and pressure values of the incoming fuel-oxidizer mixtures were such that the mixtures were self-igniting for combustor pressures above 110 bar. In other words, it was sufficient for the laser igniter to extend ignition up to 110 bar.

3. LASER IGNITER DESIGN

Subsequently, a laser igniter was designed (see Figure 3) based on the findings of the CFD simulations. A Nd:YLF laser was chosen that was capable of pulsed operation at 1053 nm, $M^2 < 3$, and having a pulse width < 7ns. In order to achieve the gas break down threshold of 200 GW/cm^2, for the intended 51 and 165 mm distance of ignition kernels from the focusing optic, a laser power of 60 mJ/pulse was required. A telescoping arrangement allowed automatic alignment of the laser head with the focusing optic, and easy variation of the ignition location (focal length) from 51 to 165 mm. A photo diode installed on the walls of the laser allowed temporal tracking of the firing of a laser pulse.

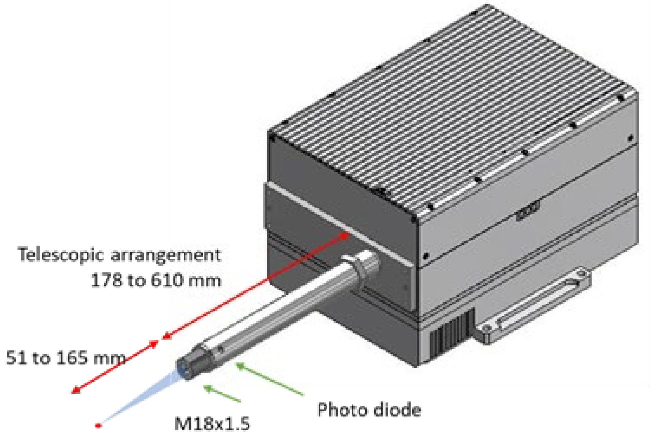


Figure 3 sCO2 combustor laser igniter.

4. BENCH_SCALE TESTING FOR PERFORMANCE EVALUATION.

At the time of the writing of this manuscript, access to a full 50 MW combustor was not available. As a result, the igniter was tested for performance in a lab-scale quiescent chamber heated to 70°C by electrical heaters. This chamber was made of a block of Titanium (see Figure 4) with a 0.5" diameter cavity at the center that enabled simulating the supercritical conditions along the line of sight of the laser. The laser igniter was placed at one end of the quiescent chamber along with an appropriate seal. One side of the chamber carried a sapphire window that provided 12.5 mm x 125 mm optical access for imaging of the ignition kernels. An image intensified camera (Princeton Instruments ICCD-MAX) enabled capturing the images of ignition kernels with an exposure time of 1 μs at appropriate time delays.

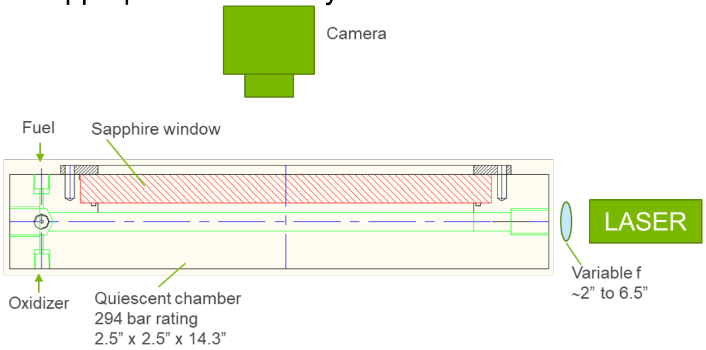


Figure 4 Test arrangement for igniter testing.

Using this arrangement, three sets of tests were performed, which are discussed below.

4.1 Non-combusting environments (compressed air)

Initial tests were performed in compressed air while varying the chamber pressure up to 160 bar. It was noticed that for a single laser pulse, multiple (up to 10) plasma kernels form along the path of the laser beam close to the focal point. The images shown in Figure 5 are composites of 20 laser pulses. As shown, in the case where a focal length of 150 mm has been used, the plasma kernels are spread out over a longitudinal length of ~25 mm. This spatial distribution of the plasma kernels assists in the energy transfer to the surrounding fluid to transition to a self-sustaining flame front, and as shown later significantly improves the ignition probability.

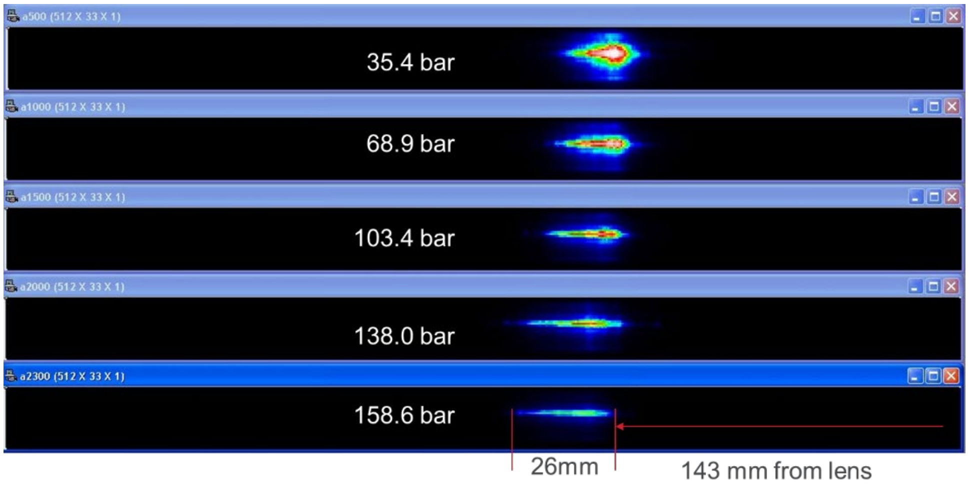


Figure 5 Laser initiated plasma kernel images in compressed air. Focal length = 150 mm; Composite image of 20 shots, exposure time = 1μs. The laser propagation is from right to left.

Also noticeable is the fact that as the pressure increases, optical scattering losses increase, making the plasma kernel weaker at higher pressures. However, the distance of the ignition kernel from the focusing optic was found to be steady within a few millimeters.

4.2 Non-combusting environments (pressurized CO_2)

As mentioned before, CO_2 concentrations within the combustor can reach up to 90% vol. To evaluate the igniter performance in pure CO_2 (i.e., 100% vol.) especially for pressures into the supercritical conditions, a steel alloy pressure vessel heated to 70^{o}C was used. Blocks of dry ice were enclosed in the pressure vessel and allowed to sublimate over time. Pressurized CO_2 so generated was routed to the quiescent chamber for laser ignition kernel imaging. Subsequently, imaging was performed for pressures up to 110 bar. It was observed that with increasing pressure the ignition kernel moved closer to the laser and also became weaker. At 41 bar a second ignition kernel (probably a second longitudinal mode from the laser) appears which also moves closer to the laser and becomes weaker in intensity as the pressure increases.

The ignition kernel location plotted as a function of pressure is shown in Figure 6. This behavior is of concern for a given laser igniter design as the ignition plasma kernel, depending on the pressure, may form at a location that cannot ensure successful ignition.

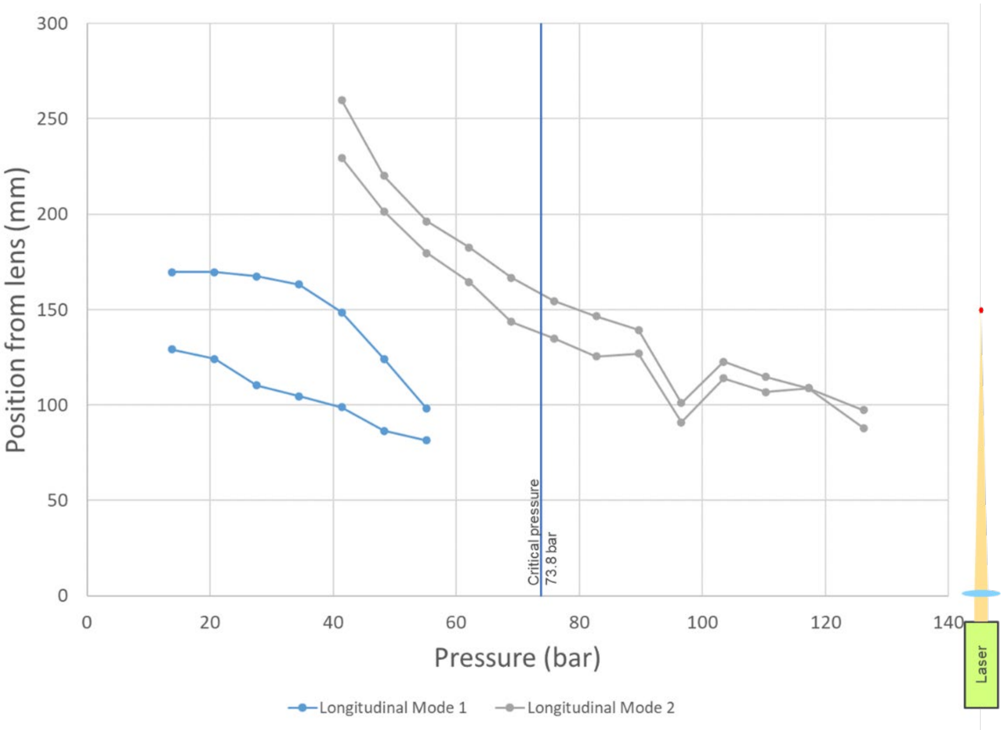


Figure 6 Ignition kernel location in pressurized carbon dioxide at 70oC. Focal length = 150 mm.

The observed pressure dependency can only be explained by the optical non-linearity of carbon dioxide. Mareev et al. have performed molecular modeling and experiments [10, 11] to study the optical properties of supercritical carbon dioxide. They have shown that refractive index can be represented as

$$n = n_o + \Delta n \cdot |E|^2, \tag{1}$$

where, E is the electric field strength, n_o the linear refractive index and Δn the non-linear refractive index. For CO_2 both indices were found to vary significantly with pressure. As explained in reference [11], for significant value of Δn, and Gaussian beam cross-sections, overall refractive index is higher towards the center of the beam as compared to that near the edges. This results in a self-focusing effect making the laser beam converge at distances much shorter than the focal length of the converging optic. To evaluate the extent of this self-focusing effect in sCO_2 combustors, where fuel and oxygen are also the fluid constituents, ignition tests were performed using fuel-oxidizer mixtures that are typical of sCO_2 combustors. These are discussed in section 4.3.

4.3 Combustion environments - Coal-derived syngas mixtures

The fuel-oxidizer mixtures were prepared by mixing the constituents in a constant volume pressure vessel while measuring the partial pressures using high-accuracy pressure transducers. The compositions of the coal-derived syngas fuel, and oxidizer used for this study are as shown in Table 1.

Table 1 Component mole fractions for fuel and oxidizer.

	Fuel	Oxidizer
CH_4		
CO_2	0.139	0.765
CO	0.608	
H_2	0.253	
O_2		0.235

To keep the combustion temperatures low, and thereby enhance the life of the combustion liner, significant amounts of CO_2 are added to both the fuel stream and the oxidizer stream. As reported in reference 2, the presence of hydrogen makes these fuel-air mixtures exhibit a wide ignitability range, $0.7 < \phi < 1.6$ with laser ignition (where ϕ is the equivalence ratio). At these extremes, the CO_2 concentrations are still noticeably high – 59% vol. for $\phi = 0.7$ and 47% vol. for $\phi = 1.6$.

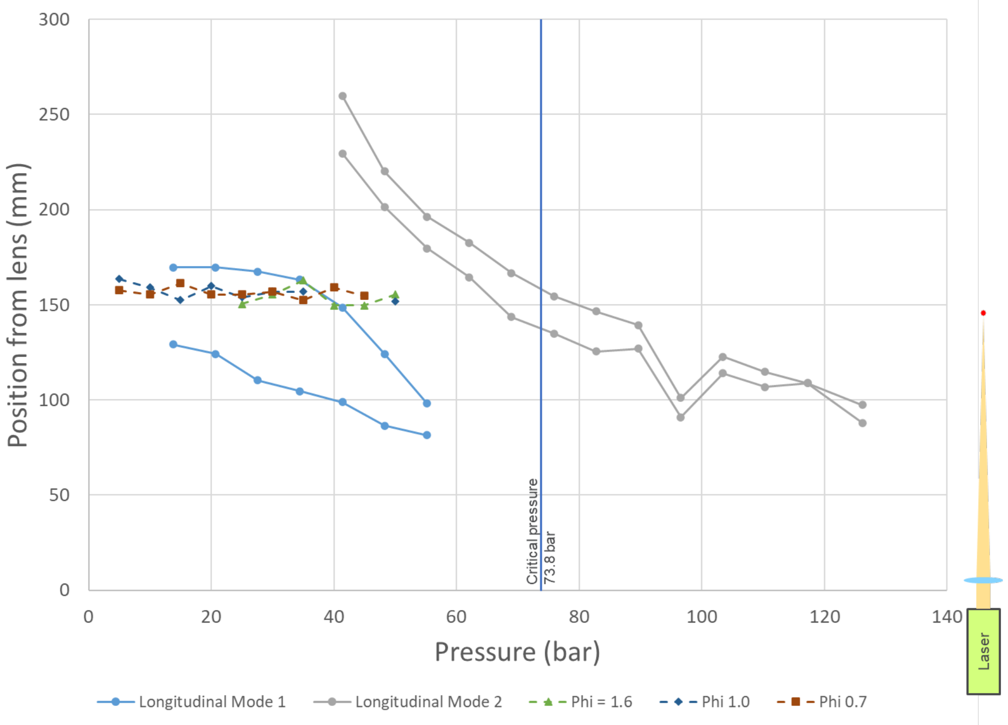


Figure 7 Ignition kernel positions in supercritical CO2. Test results for fuel-oxidizer mixtures for ϕ of 0.7, 1.0 and 1.6 are superimposed.

The observed ignition kernel position for the three equivalence ratios of $\phi = 0.7$, 1.0 and 1.6, are shown in Figure 7 overlayed over the observed positions of the ignition kernel in pure CO_2 which were shown previously in Figure 6. From these observations it is apparent that for potential fuel-oxidizer mixtures that are used in the sCO_2 combustors, the optical non-linearity of CO_2 will not have a significant effect, and the ignition kernels materialize close to the optical focus of the converging optic.

5. VARIABLE FOCUS LASER IGNITER

An ideal igniter in a sCO2 environment is expected to work reliably in a variety of combustor designs and operating conditions. However, the axial and radial dilution of the sCO_2/fuel-oxidizer mixture can vary considerably. For a given combustor geometry and spatial placement of the injectors (axial and radial) and flow rates of the dilution sCO_2 and fuel/oxidizer mixtures the local mixture equivalence ratio varies considerably. Flow fluctuations due to turbulence also result in spatial and temporal variation of the mixture equivalence ratios. A laser using a fixed focal length at a given radial location on the casing of the combustor can thus have limited capability in achieving ignition, as the focal volume may not have an ignitable mixture at all instants of time. Using a laser with a variable focal length, multiple ignition kernels can be placed at several radial locations thus greatly increasing the probability of ignition.

Such a variable focal length laser igniter is currently under development at Argonne. Such an igniter (see Figure 8) while operating the laser in burst mode enables spreading the ignition kernels over a spatial region that is 3.5 times larger than that provided by a fixed focal length laser igniter. The extended spatial and temporal distribution provided by this igniter significantly improves ignition probability.

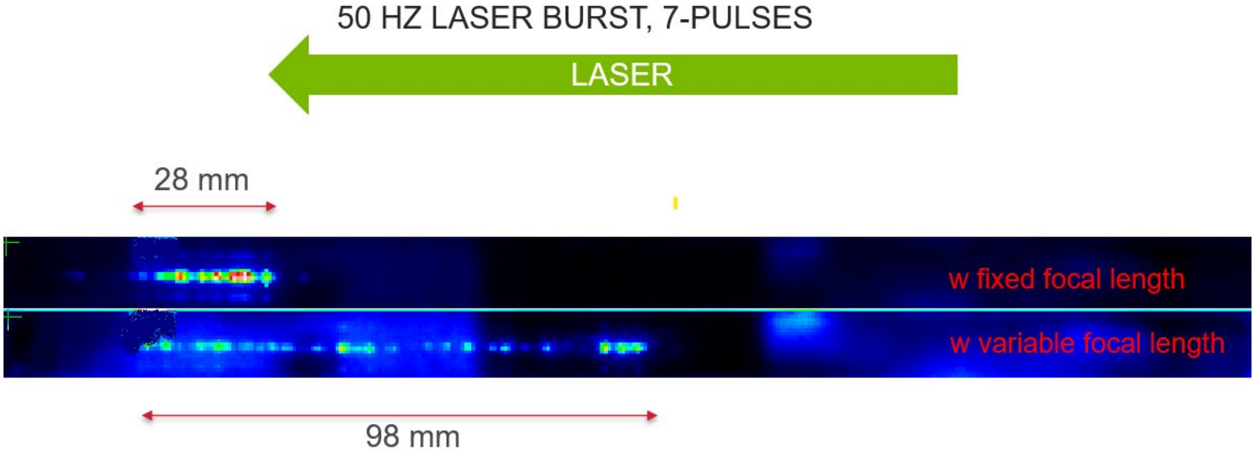


Figure 8. Images of ignition kernels by fixed focal length laser igniter and that by a variable focal length laser igniter in CO_2 at 21 bar.

6. CONCLUSIONS

In our earlier work that is reported in reference 2, CFD simulations of the flow fields inside a 50 MW sCO_2 combustor were used to guide the development of a laser igniter. For the focal length range of 50 mm to 162.5 mm required for these combustors, multiple plasma kernels formed close to the focal point. In addition to this spatial distribution, temporal distribution provided by operating the laser in a burst mode significantly improved ignition probability.

However, as carbon dioxide is used as the operating fluid and further added to the fuel and oxidizer streams as a diluent to reduce peak combustion temperatures, its local concentration within these combustors can be significantly large (up to 90 % by vol.). In the work reported in this paper, potential effect of the optical nonlinearity of carbon dioxide on the operation of the laser igniter was studied. Non-combusting tests performed in pure CO_2 showed the focal spot to shift closer to the focusing optic as the pressure increased.

Combustion tests were also performed for initial pressures up to 50 bar while using syngas-oxidizer mixtures for $\phi = 0.7$, 1.0 and 1.6. These tests showed that the effect due to optical non-linearity of carbon dioxide to be relatively weak as not to be of concern (see Figure 7). These observations confirm the robust performance of Argonne's laser igniter under all possible mixture conditions in a sCO_2 combustor.

To accommodate combustors where the flow field information is not known a priori, or wherein the flow field fluctuates significantly, a laser igniter whose focal length could be varied in-situ is also being developed. While using the laser in a burst mode this design allows spatial distribution of the ignition kernels to improve ignition probability significantly.
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