N95- 70867

Density and Mixture Fraction Measurements in a GO_2/GH_2 Uni-Element Rocket Chamber

M. D. Moser, S. Pal and R. J. Santoro

Propulsion Engineering Research Center
and
Department of Mechanical Engineering
The Pennsylvania State University
University Park, Pennsylvania 16802

Introduction

In recent years, there has been a renewed interest in gas/gas injectors for rocket combustion. Specifically, the proposed new concept of full-flow oxygen rich preburner systems calls for the injection of both oxygen and hydrogen into the main chamber as gaseous propellants. The technology base for gas/gas injection must mature before actual booster class systems can be designed and fabricated. Since the data base for gas/gas injection is limited to studies focusing on the global parameters of small reaction engines,[1,2] there is a critical need for experimental programs that emphasize studying the mixing and combustion characteristics of GO_2 and GH_2 propellants from a uni-element injector point of view. The experimental study of the combusting GO_2/GH_2 propellant combination in a uni-element rocket chamber also provides a simplified environment, in terms of both geometry and chemistry, that can be used to verify and validate computational fluid dynamic (CFD) models.

Over the past few years at Penn State, an experimental research program has focused on characterizing uni-element rocket chamber flowfields. This research has been undertaken as part of the Propulsion Engineering Research Center (PERC) at Penn State under the sponsorship of NASA. The research for this program has been conducted at the Cryogenic Combustion Laboratory at PERC, which has the capability to handle gaseous and liquid oxygen (GO_2 and LOX) as well as gaseous hydrogen (GH_2), methane and hydrocarbon fuels at flowrates comparable to single element conditions typical of rocket injectors. The work described here focuses on flowfield measurements in a uni-element (shear coaxial injector) optically accessible rocket chamber that utilizes the GH_2/GO_2 propellant combination. To date, several laser-based diagnostic techniques, including planar laser induced fluorescence (PLIF) for OH-radical fluorescence measurements,[3] laser Doppler velocimetry (LDV) for velocity field measurements,[3] and planar laser light scattering for average density and mixture fraction measurements[4] have been employed towards characterizing the combusting flowfield. The experimental results of the light scattering technique are summarized in this manuscript.

Experimental

The experiments were conducted in an optically accessible rocket chamber at Penn State's Cryogenic Combustion Laboratory. This facility is capable of supplying gaseous hydrogen (GH_2), gaseous oxygen (GO_2) and liquid oxygen (LOX) at flowrates up to 0.11 kg/s (0.25 lb/s), 0.045 kg/s (0.1 lb/s) and 0.45 kg/s (1.0 lb/s), respectively. The rocket chamber is modular in design

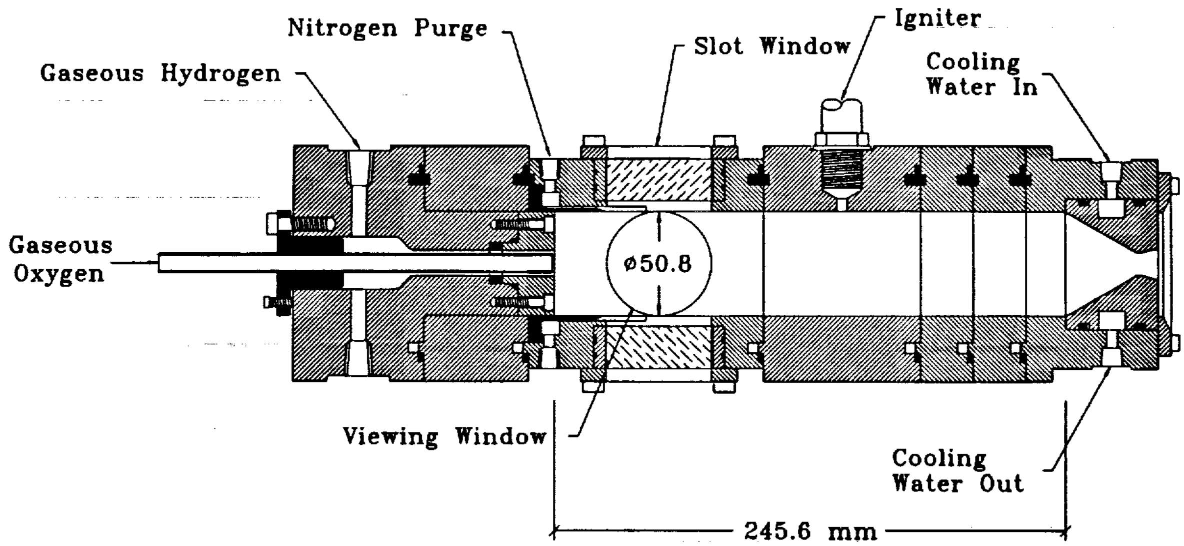

Fig. 1. Cross-sectional view of the optically accessible rocket chamber. The interior of the chamber is 50.8 x 50.8 mm.

and can be easily configured to provide optical access along the chamber length. A cross-sectional view of the rocket assembly is shown in Fig. 1. The design of the rocket chamber is detailed in Refs. 3 and 5. The chamber is comprised of several sections which include an injector assembly, igniter, window and blank sections, and a nozzle assembly. The window-section allows optical access into the combustion chamber for laser-based diagnostic techniques. Two diametrically opposed windows, 50.8 mm (2 in.) in diameter and 25.4 mm (1 in.) thick, provide optical access into the 50.8 mm (2 in.) square rocket chamber. Two slot windows measuring 6.25 x 50.8 mm (0.25 x 2 in.) on the remaining two sides provide additional optical access into the rocket chamber for laser sheet diagnostics. All windows are protected from the hot combustion gases by a gaseous nitrogen (GN_2) purge which flows across the interior window surfaces.

A shear coaxial injector introduced the propellants into the rocket chamber. The GO_2 post of the injector had an inner diameter of 7.75 mm (0.305 in.) and was flush with the injector face. The inner and outer diameters of the fuel annulus were 9.53 mm (0.375 in.) and 12.7 mm (0.5 in.), respectively. The nominal mass flowrate of GO_2 through the central tube of the shear coaxial injector was 0.042 kg/s (0.093 lb/s) while the GH_2 mass flowrate through the annulus of the injector was 0.010 kg/s (0.023 lb/s) resulting in an O/F mass flowrate ratio of four. The nozzle had a throat diameter of 11.35 mm (0.447 in.). The flowrates together with the nozzle configuration produced a chamber pressure of 1.31 MPa (190 psia). The c^* efficiency of the rocket firings is close to 98%.[3]

Laser light scattering from seed particles was used for studying the mixing characteristics of the GH_2/GO_2 combusting flowfield. The technique involves seeding each of the propellant streams individually with sub-micron Al_2O_3 particles, illuminating the flowfield with a laser sheet, and recording the scattered light. Since the seed particle mark the seeded propellant stream, measurements of scattered light, which is proportional to the seed concentration, can be used to extract information on the mixture fraction, density, species concentration and temperature.[6,7,8]

Fig. 2. Instantaneous image of light scattered from Al_2O_3 particles seeded in the oxygen flow. Field of view is from the injector face to 45.7 mm downstream.

Results and Discussion

Multiple (~ 100) instantaneous planar images of light scattered from particles individually seeded into the GO_2 and GH_2 flows were obtained downstream of the injector face. A typical instantaneous light scattering image with the oxygen flow seeded is shown in Fig. 2. Here, the injector is at the left edge of the image and flow is from left to right. The normalized intensity, f_O, relates scattered light intensity, I, to density, ρ, and mixture fraction, ξ, by the following relation:

$$f_O = \frac{I}{I_O^\circ} = \frac{\rho(1-\xi)}{\rho_O^\circ(1-\xi^\circ)} \tag{1}$$

where I_O°, ρ_O°, and ξ° are intensity, density, and mixture fraction at a reference point, typically at the injector exit. Similarly, for the GH_2 seeded flow the following relation is obtained:

$$f_F = \frac{I}{I_F^\circ} = \frac{\rho\xi}{\rho_F^\circ \xi^\circ} \tag{2}$$

The average density in the flowfield was obtained from combining the averaged light scattering images of both the GH_2 and GO_2 seeded flows. The radial profile of average density at an axial distance of 25.4 mm (1 in.) from the injector face is compared to predictions made using the FLUENT code[9] in Fig. 3. The average density is maximum at the centerline, corresponding to the region of high oxygen concentration, and decreases with radial distance. The experimental results and code predictions agree reasonably well in terms of both maximum density and radial profile symmetry in the central region of the flowfield. However, away from the centerline, the average density does not drop off to the low values predicted by the code.

Density, mixture fraction and other parameters are derived from the individually seeded GO_2 and GH_2 scattered light images with a function relating these parameters to the product of the density and mixture fraction, $\rho\xi$. An example of such a relationship, calculated with the Chemical Equilibrium Calculation (CEC) program[10] assuming equilibrium, is shown in Fig. 4. The results of applying this function to the GH_2 seeded data and a similar function to the GO_2 data is shown in Fig. 5. The width of the high density region is greater for the results obtained from the GO_2 seeded data than for the GH_2 seeded data. In comparing Fig. 3 with Fig. 5, it is evident that the radial profile of average density obtained using averaged images is closer to that

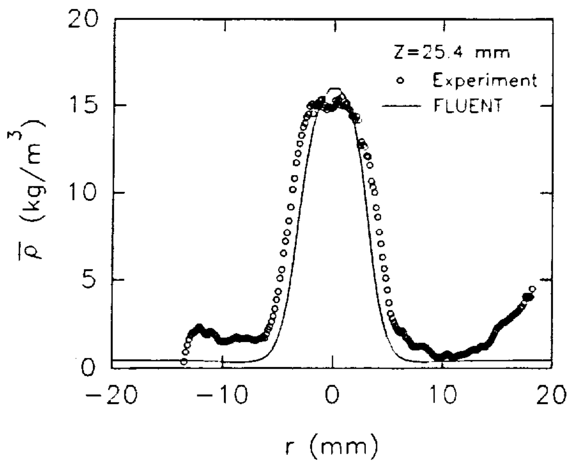

Fig. 3. Average density vs. radius at an axial distance of 25.4 mm from the injector face. Density derived from averaged light scattering images is compared with predictions made using the FLUENT code.

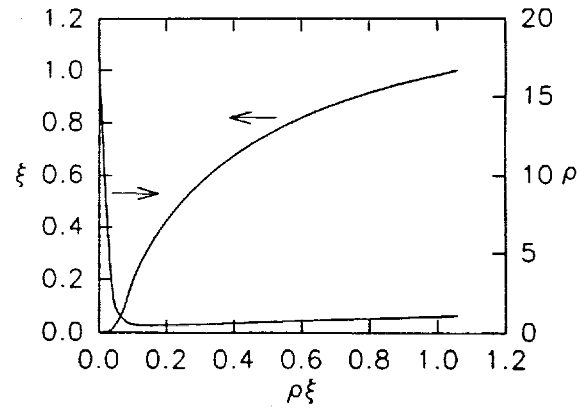

Fig. 4. Functional dependency of density, ρ, and mixture fraction, ξ, on the product, $\rho\xi$, calculated using the Chemical Equilibrium Calculation (CEC) program (Gordon and McBride [10]).

obtained using the GO_2 seeded scattered light images than the GH_2 seeded scattered light images. However, away from the centerline, the average density obtained from the GH_2 seeded scattered light images matches the code predictions.

Conclusions

Planar laser light scattering images from individual seeding of both the GO_2 and GH_2 flows depict the unsteady nature of the reacting flowfield. The direct analysis of these images provided estimates of the average density and Favre averaged mixture fraction fields in the flowfield. Estimates of average density derived by applying the equilibrium relationships to either the GH_2 or GO_2 seeded flows should yield similar results, except in regions of low signal to noise due to low seed number densities. The causes of the discrepancies observed in Fig. 5 could be due to either effects of flow conditions (i.e. the ability of the seed to follow the flow, or temperature effects) or to the data reduction methodology. These effects are being assessed through cold flow and hot fire tests with methane and oxygen.

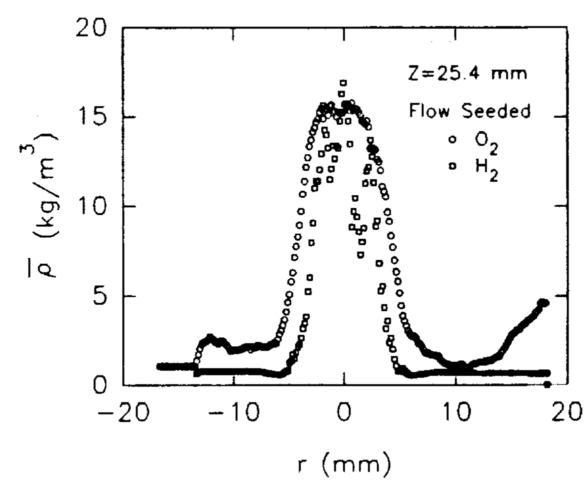

Fig. 5. Average density at an axial distance of 25.4 mm from the injector face. The radial density profiles are derived from scattered light images of both GO_2 and GH_2 seeded flows with the assumption of local equilibrium.

Acknowledgment

Funding by NASA Marshall Space Flight Center, Contract NAS 8-38862 and the Penn State Propulsion Engineering Research Center, contract NAGW 1356 Supplement 5, is acknowledged. The authors thank Mr. D. Harrje for his insightful comments and suggestions in the design of the Cryogenic Combustion laboratory and uni-element rocket chamber. The authors also thank Mr. L. Schaaf for his help in conducting the experiments.

References

1. Paster, R. D., "Hydrogen Oxygen APS Engines (High Pressure)," Contract NAS3-14352, Rocketdyne Report R8837-1, NASA CR- 12085.

2. Johnson R. J., "Hydrogen-Oxygen Catalytic Ignition and Thruster Investigation, Vol. I: Catalytic Ignition and Low Pressure Thruster Evaluations," Contract NAS3-14347, TRW Report 14549-60010-RO-00, NASA CR-120869.

3. Moser, M. D., Merenich, J. J., Pal, S., and Santoro, R. J., "OH-Radical Imaging and Velocity Field Measurements in a Gaseous Hydrogen/Oxygen Rocket," AIAA 93-2036, AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit, Monterey, CA, June 28-30, 1993.

4. Moser, M. D., Pal, S., and Santoro, R. J., "Uni-Element Rocket Studies," 1994 Conference on Advanced Earth-to-Orbit Propulsion Technology, NASA Marshall Space Flight Center, AL, May 17-19, 1994.

5. Pal, S., Moser, M. D., Ryan, H. M., Foust, M. J. and Santoro, R. J., "Flowfield Characteristics in a Liquid Propellant Rocket," AIAA 93-1882, AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit, Monterey, CA, June 28-30, 1993.

6. Stepowski, D., and Cabot G., "Laser Mie Scattering Measurement of Mean Mixture Fraction Density and Temperature by Conditional Seeding in a Turbulent Diffusion Flame," Twenty-Second Symposium (International) on Combustion, The Combustion Institute, pp. 619-625, 1988.

7. Kennedy, I. M., and Kent, J. H., "Measurements of a Conserved Scalar in Turbulent Jet Diffusion Flames," Seventeenth Symposium (International) on Combustion, The Combustion Institute, pp. 279-287, 1979.

8. Stepowski, D., "Laser Measurements of Scalars in Turbulent Diffusion Flame," Prog. Energy Combust. Sci., Vol. 18, pp. 463-491, 1992.

9. FLUENT Computer Program from Fluent, Inc.

10. Gordon, S. and McBride, B. J., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations," NASA SP-273 Interim Revision N78-17724, March, 1976.