Combustion of Porous Graphite Particles in Oxygen Enriched Air[1]

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OBJECTIVES:
Combustion of solid fuel particles has many important applications, including power generation and space propulsion systems. The current models available for describing the combustion process of these particles, especially porous solid particles, include various simplifying approximations. One of the most limiting approximations is the lumping of the physical properties of the porous fuel with the heterogeneous chemical reaction rate constants [1]. The primary objective of the present work is to develop a rigorous modeling approach that could decouple such physical and chemical effects from the global heterogeneous reaction rates. For the purpose of validating this model, experiments with porous graphite particles of varying sizes and porosity are being performed under normal and micro gravity.

EXPERIMENTAL APPROACH:
As reported in the previous Microgravity Workshop [2], the major experimental challenges of this project were particle deployment, ignition, and obtaining *self-sustained oxidation* under normal and reduced gravity conditions. The typical char particle temperature that support self-sustained oxidation is over 1600 K [3]. In practical coal combustors, because of the high temperature environment containing oxygen and hot vitiated products, porous char particles undergo self-sustained oxidation. Replicating such an high temperature environment in reduced gravity facilities is difficult and has not been pursued yet. The main challenges of creating an high-temperature environment in microgravity are related to the temperature decay due to heat losses (during 20 seconds of reduced gravity in KC135 aircraft) and avoiding buouyancy driven currents in the process of creating high-temperature environment.

(i) An Alternate Method of Self-Sustained Oxidation: O_2 Enrichment:
In air at room temperature, the convective and radiative heat losses from the particle to the surroundings are significant compared to the heat release; consequently, self-sustained combustion was never realized. In addition, the heat losses associated with particle mounting can further inhibit the particle oxidation. Under such conditions, an external energy source in the form of a focused CO_2 laser beam, with a minimum heat flux of 88 W/mm^2 was needed to burn the particle in less than 25 secs.

In order to attain self-sustained heterogeneous combustion of porous carbon particles, oxygen enriched air was considered. With the enclosed chamber designed for this project [4], under normal and reduced gravity room temperature conditions enriched air provided self-sustained combustion when the oxygen mass fraction was above 55%. Similar enriched conditions were used by Ubhayakar and Williams [5], in the context of combustion of a coal char particle (about 125 microns in diameter) under normal gravity conditions.

(ii) KC135 Aircraft Experimental Setup:
The first KC135 reduced gravity experiments with 1 mm size porous carbon spheres (porosity

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31%) in air were performed in October 2001, with follow-up experiments in oxygen enriched air in March and April 2002 [6]. The experimental rig consists of an enclosed chamber certified for pure oxygen environment, CO_2 laser and associated optics for rapid particle ignition, Cohu monochrome camera with an Optem Zoom70 microscope lens, together with a Mini-DV recorder to record the particle image at 30 fr/s (adequate for carbon particle oxidation with burning rate constants of the order of 0.1 mm^2/s), fiber optic coupled spectrometer for particle temperature measurement, and oxygen sensor to monitor the enrichment level. All the above components were mounted on 4ft$\times$ 2ft optical bread board, with a separate equipment rack for power supply of the laser, water cooling system for the laser, laptop, etc.

(iii) Particle Mounting:
Laser drilled porous carbon particles, tethered with a 12 micron alumina (Al_2O_3) fiber as shown in Fig. 1 were used in the present experiments. Because of the large aspect ratio (i.e. 1 mm sphere with a 15 micron diameter hole), the laser drilled holes were far from the desired 15 micron straight holes. Laser drilling of the particles were performed by several commercial vendors, as well as the NASA Glenn Research Center micromachining laboratory. In all these attempts, the drilled holes took an hour-glass shape (with 75 micron at the ends and about 50 micron at the neck hole) because of the large aspect ratio involved. To maximize the number of reduced gravity experiments in the KC135 aircraft, a rotary table with five particle holders was designed [2,6].

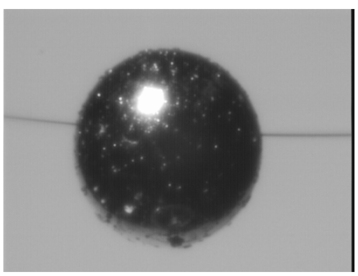

Figure 1: 1 mm carbon particle mounted on 15 μm alumina fiber [6].

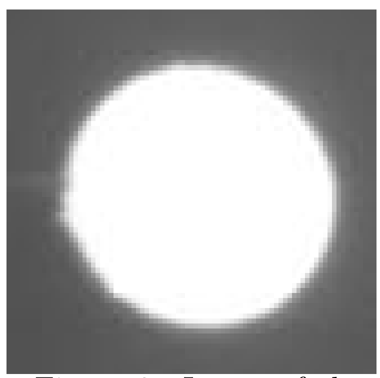

Figure 2: Image of the oxidizing particle in enriched air, using a OD 8 neutral density filter [6].

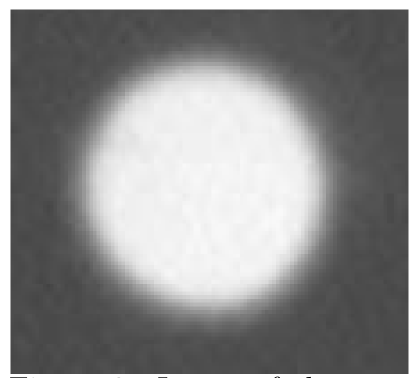

Figure 3: Image of the oxidizing particle in enriched air, using 410$\pm$ 10 nm bandpass filter [6].

(iv) Regression Rate and Surface Temperature Measurements:
Once ignited by the focused CO_2 laser beam, with a typical spot size of about 200 μm diameter, the carbon particles oxidized in about 5-10 sec in oxygen enriched air. In the past research we demonstrated the use of a microscope CCD camera for particle imaging [2] and a fiber optic coupled spectrometer to measure the particle surface temperature [7]. From the camera images, we were able to track the particle diameter vs. time using specialized tracking software developed at NASA Glenn. Unlike droplet combustion which typically uses a backlit view of the droplet, in our case the graphite particle was sufficiently self-luminous that we were able to image it directly. That led, however, to an uncertainty in the data analysis when the question arose as to whether the camera was imaging only the particle emission, or whether there could have been an influence of a CO gas-phase flame that changed the apparent particle size. Limited tests with optical filters (eg. OD 8 neutral density filter to reduce broad-band

emission vs. 410±10 nm band-pass filter to capture CO emission) failed to conclusively answer this question. Figure 2 shows an image of the luminous particle obtained with the OD 8 neutral density filter, while Fig. 3 shows that obtained with 410 nm band-pass filter. The latter shows a more diffusive image, indicative of the CO diffusive-reactive layer outside the particle.

A miniature fiber-optic coupled spectrometer (Ocean Optics S2000) was used to acquire the emission spectrum from the particle in order to determine its temperature. This method requires only that the particle emissivity be constant over the spectral region measured, but not necessarily a black body. The recorded spectral emission in the range from 767 to 937 nm was considered, with fitting the resulting intensity vs. wavelength data to a black body curve to obtain the temperature. To obtain the spectrometer sensitivity function, it was used to measure a calibrated black body source at 1000^{o}C [6].

(v) Experimental Results:
Figure 4 shows the variation of the square of the normalized particle diameter vs. time, for three enriched air experiments (60%, 65% and 70% oxygen) at room temperature, with glassy carbon spheres (31% porosity) under normal gravity. These experiments were performed with the 410 nm band-pass filter. The increase of the slope of the line with increasing O_2 level indicates a distinct effect on the mass burning rate with oxygen concentration. This means the combustion is in a diffusion-controlled regime, which is expected for the large particle size. When oxygen mole fraction was below 55%, no emissions were observed indicating that self-sustained oxidation is not possible. Limited porous carbon particle oxidation experiments were performed under reduced gravity conditions, under similar oxygen enrichment conditions. After each burn in the KC135 aircraft, a fresh particle on the rotary table was brought into a preselected position in the camera field of view and the laser focus. However, minute shifts of the

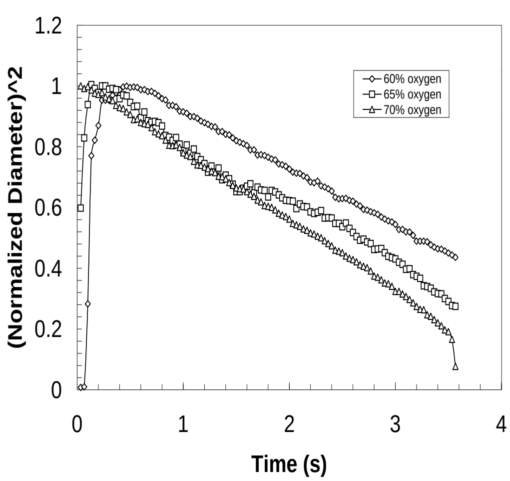

Figure 4: Comparison of the normalized equivalent particle diameter square vs. time, for oxygen enriched air under normal gravity.

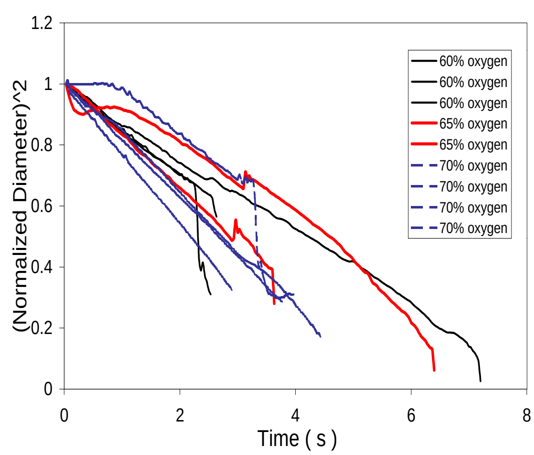

Figure 5: Comparison of the normalized equivalent particle diameter square vs. time, for oxygen enriched air under reduced gravity.

particle requiring fine adjustments of the CO_2 laser and camera, necessitated the use of OD 8 neutral density filter in reduced gravity experiments, instead of the 410 nm band-pass filter used in normal gravity.

As expected, the carbon particles oxidized in enriched air without any difficulty in reduced gravity, as shown in Fig. 5. Analysis of these data have indicated a slightly lower burning rate constant compared to the normal gravity conditions. However, the results shown in Fig. 5 indicate no clear trend with oxygen enrichment, as summarized in Table 1. Also the results shown in Fig. 5 indicate abrupt changes at some instances in time. These sudden changes are believed to be due to *g*-jitter effects, but for these preliminary experiments we had no accelerometer data. Even at these highly enriched air conditions, it is clear that the reduced gravity oxidation time exceed that of the NASA 5.2 sec drop tower. Considering the initial transition effects associated with particle heat up and ignition, the KC135 aircraft is the best choice for experiments with solid fuel particles.

Table 1: A Preliminary Comparison of Particle Burning Rate Const. (mm^2/s)

Oxygen mole fraction in air	60 %	65%	70%
1g experiments (with 410 nm filter — Fig. 4)	0.189	0.210	0.231
1g experiments (with the OD 8 neutral density filter)	0.191	0.162	—
reduced g experiments (with the OD 8 neutral density filter — Fig.5)	0.140	0.137	0.147

NUMERICAL APPROACH:

The details of the *unsteady* solid particle combustion model that is being developed were presented at the previous microgravity workshop [8]. The goal of this effort was to (a) couple the internal pore combustion to external homogeneous combustion, (b) develop a set of consistent inter-phase conditions for scalar variables, (c) investigate the transient effects, including extinction of particle oxidation, and (d) validate the model with experimental data. While the unsteady model predicted the ignition and subsequent quasi-steady state oxidation process comparable to early experiments, calculations have not been performed for the oxygen enriched air at room temperature. Because the experiments indicate a quasi-steady burning trend, for both normal and reduced gravity, the goal here is to first perform the quasi-steady modeling calculations first as described by Chelliah [3], before undertaking the computationally expensive transient calculations.

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