HETEROGENEOUS COMBUSTION OF POROUS GRAPHITE PARTICLES IN NORMAL AND MICROGRAVITY [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 model 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. The details of this experimental and theoretical model development effort are described below.

EXPERIMENTAL APPROACH: As reported in previous Microgravity Workshops [2,3], the major experimental challenges of this project were particle deployment, ignition, and obtaining self-sustained combustion under normal and reduced gravity conditions. Four types of porous particles were considered in previous tests, but only results with glassy carbon spheres are reported here.

(i) Methods of Enhancing Particle Oxidation: Because of heat losses from the hot particle to room temperature air, and particle mounting techniques used, self-sustained combustion was never achieved in previous experiments. An external energy source in the form of a focused CO2 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, methods of enhancing the particle combustion were pursued recently, namely (a) using enriched air and (b) vitiated air. With the new enclosed chamber designed [4], under normal gravity and room temperature conditions, enriched air provided clear evidence of self-sustained combustion. 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. The first microgravity experiments with the present setup, involving 1 mm size glassy carbon spheres in enriched air conditions are to be conducted in the KC135 aircraft in April/May, 2001, and a followup experiment is planned in June. As shown in Fig. 1, this modified experimental rig consists of an enclosed chamber, CO2 laser and associated optics, camera, spectrometer, and oxygen sensor, all mounted on 4'$\times$2' optical bread board, with a separate equipment rack for power supply of the laser, image recording system, etc.

(ii) Particle Deployment: After considerable effort and testing of various particle mounting approaches, the challenge of keeping the particle in the camera field-of-view (FOV) during oxidation and minimization of heat losses was accomplished by using laser drilled particles, tethered with a 12 micron alumina (Al2O3) fiber. 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

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micron at the ends and about 50 micron at the neck hole) because of the large aspect ratio involved. Nevertheless, these particles provided a viable approach of mounting particles for microgravity experiments. At very high particle temperatures and in an oxidizing environment, typically over 2500 K (especially in air enriched with oxygen), commonly used silicon carbide (SiC) fibers failed during the combustion tests. However, Al2O3 fibers with a lower melting temperature than the SiC fibers, survived oxidation and provided the only method of keeping the particle in the FOV.

For the KC135 aircraft experiments, which typically involves a sequence of 5-10 reduced gravity parabola's, a rotary table with five particle holding mechanisms was designed, as shown in Fig. 2. This table can be remotely indexed once the chamber is filled with enriched air; hence it can remain sealed during the sequence of parabola's providing 5 experimental data points.

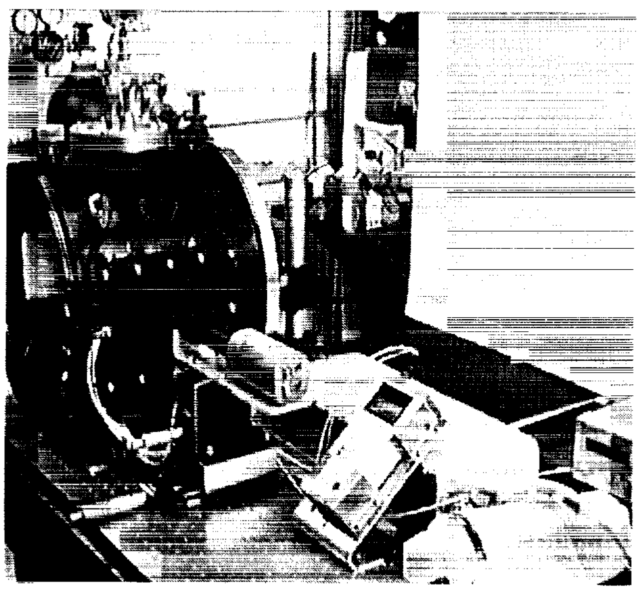

Figure 1: Photograph of the KC135 experimental setup, indicating the chamber, laser, camera, etc..

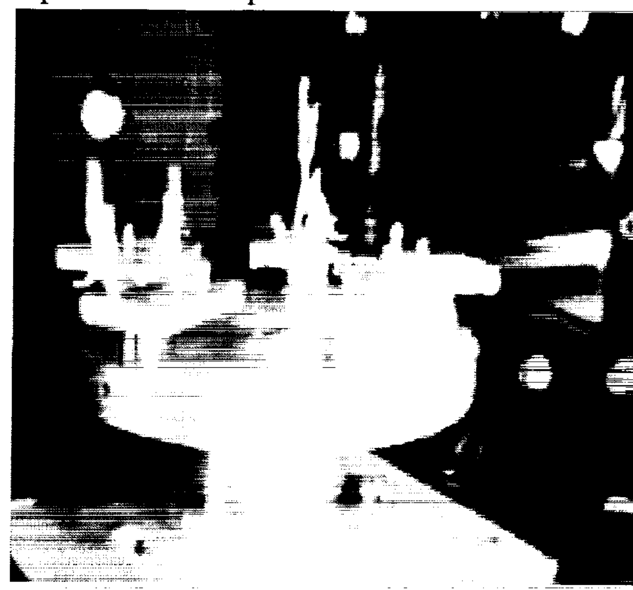

Figure 2: Rotary table with provision for holding 5 tethered particles.

(iii) Ignition: The ignition of the particle, roughly 1 mm in diameter was achieved by a 5W CO2 laser. The laser was focussed to a 200 μm diameter area and the beam intensity has been characterized previously [4]. A 10" focal length ZnSe lens held on a vertical xy-stage, with the entire assembly mounted outside the chamber allowed accurate focusing of the beam at the center of the particle. Unlike previous experiments where the particle was perched on a hypodermic needle with significant heat losses, in the present enriched air experiments with self-sustained combustion, the duration of exposure of the laser beam on the particle was very short (fraction of a second compared to combustion duration of the oder of 10 secs).

(iv) Regression Rate Surface Temperature Measurements: The self-luminous particle during combustion was previously observed directly through the optical system, which consisted of a Cohu monochrome camera with an optem Zoom70 microscope lens, together with a VCR was used to record the particle size and shape. In the present enriched air experiments, the luminosity of the particle was overwhelming and a 410$\pm$10 nm CO bandpass filter was used to record occurrence of heterogeneous combustion and the particle surface regression rate. As the combustion intensity changes, such a filtering scheme may not be ideal, especially during the initial transition stage, but here for convenience such filtered images were used to characterize the relative change in surface area

or particle size.

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 blackbody curve to obtain the temperature. To obtain the spectrometer sensitivity function, it was used to measure a calibrated blackbody source at 1000°C [6].

(v) Experimental Results: The results presented in this report were obtained under normal gravity conditions with different levels of enriched air. The corresponding reduced gravity experiments are to be conducted in April/May in the KC135 aircraft.

Figure 3 shows a comparison between the present enriched air experiments (roughly 70% oxygen, 30% nitrogen in moist conditions) and the previously reported laser supported experiments of similar glassy carbon spheres. The enriched experiments show a counter-intuitive initial increase in particle size, followed by the expected D^2-Law type reduction in its size. This perceived increase in size is perhaps due to combination of the initial increase in CO layer and the CO-bandpass filter used. Once the oxidation process is well established, the CO layer is expected to be rather narrow and adjacent to the surface and can be considered as a good marker of the measurement of surface regression rate. A close examination of the image intensity show that the edges of particle are not very sharp, indicating a somewhat broad CO oxidation layer (see Fig. 4). Such a broad CO layer may introduce uncertainties in the estimation of particle size, and methods for minimizing such errors must be developed.

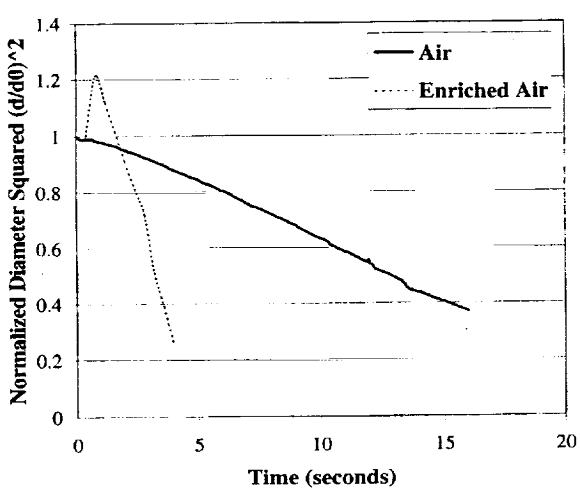

Figure 3: Comparison of the normalized equivalent particle diameter square vs. time, for normal air with laser heating and enriched air (self-sustained oxidation).

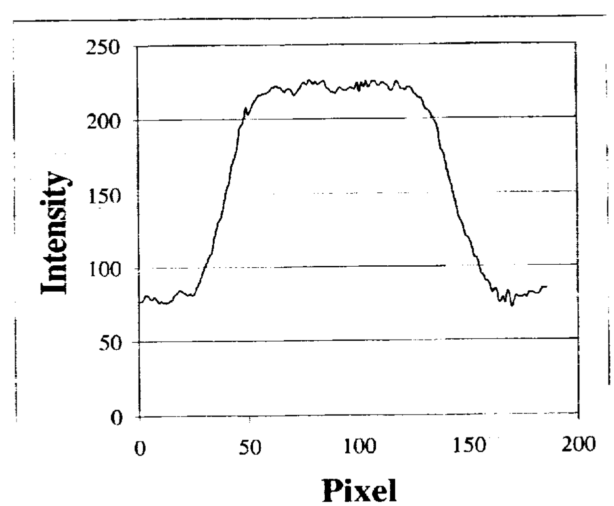

Figure 4: Recorded image intensity measurements across the particle in terms of pixels.

Clearly, the enriched self-sustaining combustion results shown in Fig. 3 indicate a much stronger oxidation of the particle, with the last image recorded indicating a particle size of about 450 microns. Whether this particle fell from the fiber support and moved out of the view of the camera or whether the combustion process extinguished must be examined carefully. The experiments by Ubhayakar and Williams [5] describe the extinction of particle oxidation as the air enrichment level is reduced, essentially supporting the concept of the existence of a critical particle size for combustion, which is the ultimate goal of the present investigation.

NUMERICAL APPROACH: The details of the *unsteady* solid particle combustion model that is being developed were presented at the previous microgravity workshop [3]. 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.

Experimental data that were available for model validation at the last workshop were obtained by continuous laser heating of the particle to compensate for the significant heat losses through the hypodermic needle [3]. These experiments also indicated a particle temperature of about 2000K. In the corresponding simulations, the laser energy deposition of about 100 W/mm^2 was included, but heat loss through the hypodermic needle was ignored because of the uncertainty associated with modeling such a loss term. However, in simulations, if a maximum particle temperature is introduced to cap the uncontrolled increase in particle temperature, then the particle regression rate predictions obtained are consistent with the experimental data ($d(d^2)/dt = 0.04 mm^2$/s). Figure 5 shows a plot of mass burning rate with the imposed temperature cap and Fig. 6 shows the corresponding variation of square of the particle radius vs. time, indicating the initial transient conditions, followed by quasi-steady oxidation. Simulations of particle oxidation under enriched air conditions are currently underway.

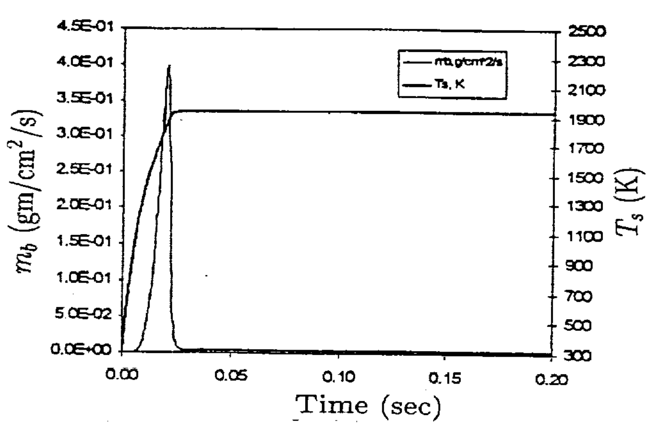

Figure 5: Variation of mass burning rate and surface temperature vs. time, with peak surface temperature around 2000 K.

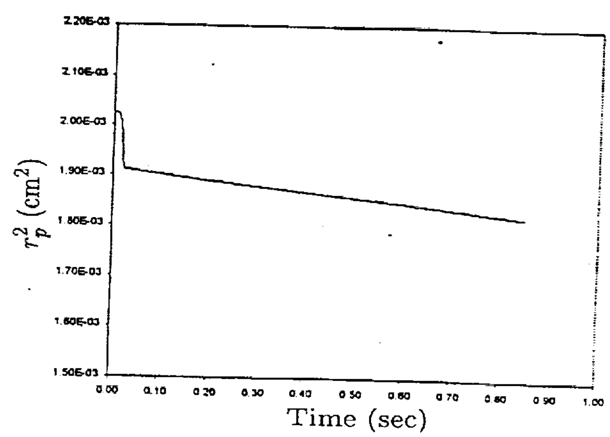

Figure 6: Corresponding square of the particle diameter vs. time, for the case in Fig. 5.

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