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DRAG COEFFICIENTS OF BURNING POLYMER SPHERES DURING FREE FALLING AT ELEVATED PRESSURES

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Photographical studies were made of the burning phenomena of carboxyl terminated polybutadiene (CTPB) and polyurethane (PU) spheres during free falling in pressurized oxidizing atmospheres (5-30kg/cm^2). Both of polymeric fuel spheres yielded several times as large drag coefficients as non-burning standard solid spheres.

Performance loss due to lag in the temperature and velocity of the condensed particles from the gaseous combustion stream at nozzle conditions, well-known as multi-phase effects, is often appreciable with solid-propellant rocket motors. The influence of multi-phase flow on hybrid-propellant motor performance should be also considered because inherently the burning reactions occur mainly in a narrow diffusion flame zone and the complete burning of fuel polymer would be incapable of being achieved without additional recombustion devices. Moreover, the liquid oxidizer stream line impinging directly on the slab surface may tear off liquid and char layer from there.

As the first step to realize the improvement in hybrid motor performance and to gain the understanding for the burning treatment of wasted polymers in a flow system this letter provides the drag coefficients of typical fuel ingredients for solid and hybrid rocket motors, i.e., carboxyl terminated polybutadiene (CTPB) and polyurethane (PU). These polymers are quite different in the burning characteristics: the former involves sparse char layer surrounding the virgin polymer during most burning period and, on the other hand, the latter burns in a similar mechanism to common distilled hydrocarbon oil droplets. Accordingly, the presence of these fuel particles in the combustion stream might introduce different multi-phase effects.

Experimental

As shown in Fig. 1, a polymer sphere is suspended with a cotton thread in a windowed high pressure chamber and ignited electrically with a nichrome fiber at the bottom side of the sphere. The thread being cut off soon after ignition, the burning polymer sphere falls freely under action of gravitation in pressurized oxidizing atmosphere. The initial sphere diameter ranges from 3 to 5mm, ambient total pressure is 5-30kg/cm^2, and the pressurized gases are 100% oxygen, O_2/Ar=80/20, 50/50 and O_2/He=80/20, 50/50.

The displacement history of the burning sphere viewable through the window (350Lx30W) is observed by a two-eyes 6x6 frame camera with the shutter opened. By

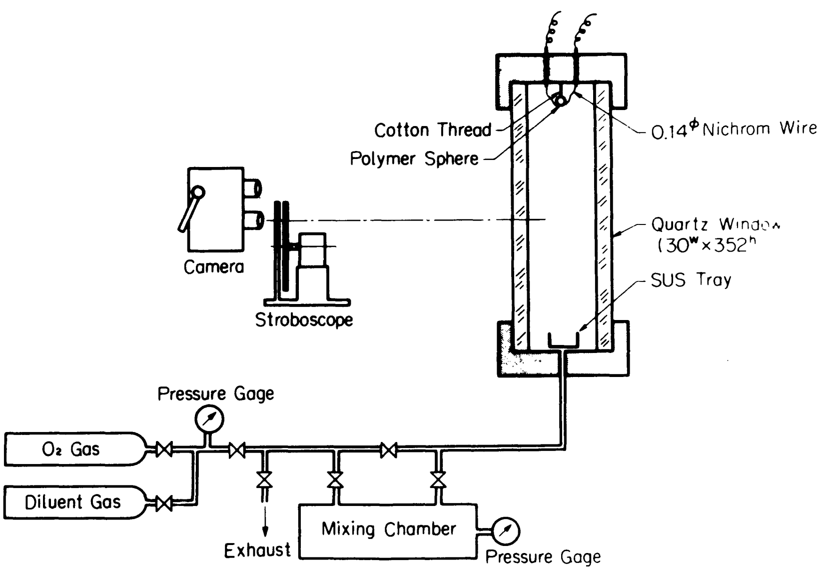


Fig. 1. Experimental apparatus.

intercepting the sphere image at the interval of 1/25 or 1/50 second in the trajectory with a light chopper, the changes of velocity and diameter are obtained. According to Newton's second law, the equation for the calculation of the drag coefficient is given as follows:

$$m\alpha = mg - f - j \qquad (1)$$

where α is the acceleration of sphere, g the gravitational acceleration, f the drag force, j the buoyancy and m is the instantaneous mass. This equation indicates that accurate measurements of instantaneous mass and rate of velocity change are required. However, in this experiment employing comparatively large size spheres, the change in mass during visible free falling of approximately 0.2 second is neglected. Substituting $m=(4/3)\pi r^3\rho_s$, $f=(1/2)\rho_g v^2 \pi r^2 C_D$ and $j=(4/3)\pi r^3 \rho_g$ into Eq. (1), we obtain

$$C_D = \frac{4d}{3v^2}\left\{g\left(1-\frac{\rho_g}{\rho_s}\right)-\alpha\right\} \qquad (2)$$

where C_D is the drag coefficient, d the sphere diameter, v the falling velocity, ρ_s and ρ_g are the density of sphere and ambient gas, respectively. As a function of Reynolds number $Re=\rho_g vd/\mu$, the effect of the gases issued from the burning surface and char layer on the drag coefficient is described. In this case, the viscosity of ambient gas μ is the value at room

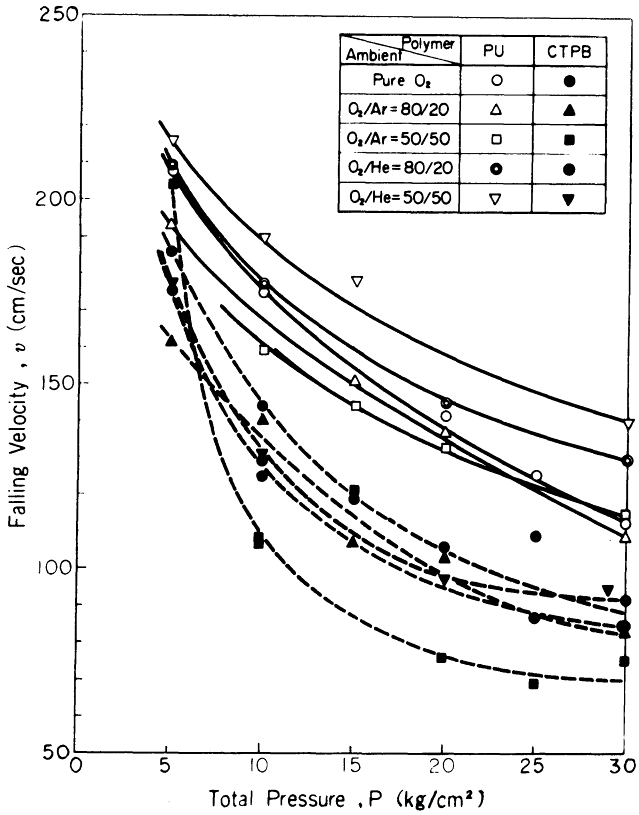


Fig. 2. Falling velocity at the position of 28 cm from initial point.

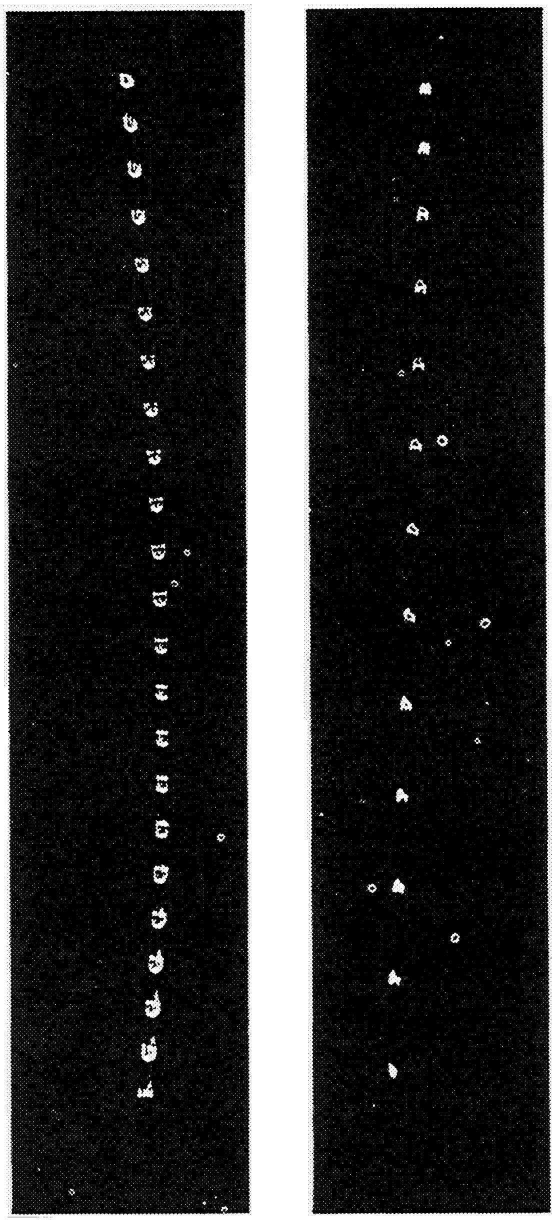
temperature and d is assumed to be the initial diameter of sphere before ignition.

Results and Discussion

Fig. 2 shows the falling velocities of the burning spheres at the position of 28 cm from the initial point. It is indicated that CTPB having thin char layer demonstrated a lower velocity by a half than PU. Ar gas diminishes the falling velocity for PU, compared with pure oxygen, while He gas makes the PU sphere accelerate and attain to the terminal velocity in longer trajectory path. This tendency seems to occur due to the difference of buoyancy between two diluents.

The CTPB sphere behaves similarly to PU in the relation between the falling velocity and the constituent of ambient gases. However, the important feature here is that, the more He gas fractions are in the mixture of oxygen, the lower the falling velocity becomes. This result may suggest that the chilling effect of He gas on the flame reaction emerged dominantly to retard the sphere velocity. In fact, under the same condition the diameter of the contact surface curvature of burned gases enveloped by ambient convection gas at $O_2/He=80/20$ is larger by about 20% than at $O_2/He=50/50$. The falling velocity of CTPB sphere gets to equilibration within 2/25 to 3/25 second at $30 kg/cm^2$. After then occasionally, a slight deceleration took place on account of changes of local burning surface situation and development of char layer which introduces the enhancement of buoyancy.

The burning sphere of PU elastomer can be assumed to be dense, so that the volumetric effects caused by complex burning surface structure as with CTPB are negligible. Therefore, the PU burning sphere has a longer trajectory path for velocity equilibration.



a) CTPB b) PU

Fig. 3. Typical free-falling trajectory of burning polymer spheres.
a) d=2.95 mm. $O_2/Ar=50/50$ at $30 kg/cm^2$. b) d=3.20 mm. Pure O_2 at $20 kg/cm^2$.

Fig. 3 represents typical free-falling trajectories of these two burning spheres, whose streaks form a striking contrast. With CTPB spheres the eruption produced by internal pressure, numerous heterogeneous flamelets above the surface and repeated swelling and contraction have resulted in a somewhat distorted falling path and higher apparent aerodynamic drag force. On the other hand, PU spheres of which burning surfaces are covered with liquid layer depict a nearly straight trajectory, so that a great part of radiative burning reaction occurs in the medium of the recirculation zone and in rapidly growing wake trail. This concentrative burning in the recirculation zone will generate impulse to make the burning sphere accelerate to some effective extent. Accordingly, the apparent drag coefficient for burning PU sphere becomes lower and approaches the level of distilled hydrocarbon droplets. However, since the enhancement of buoyancy encountered by the formation of char layer and heterogeneity of the flame structure is not taken into consideration in Eq. (2), the derived drag coefficient for CTPB sphere appears to yield an overestimated value.

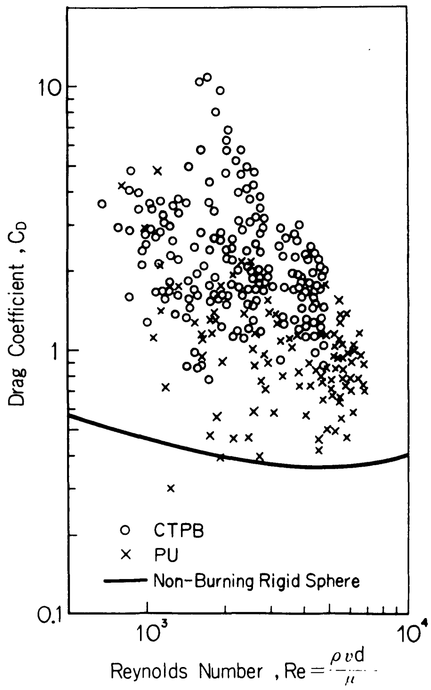


Fig. 4. Drag coefficient of burning polymer spheres.

Fig. 4 is a plot of the drag coefficients of PU and CTPB spheres on which the standard drag coefficient curve for rigid sphere in steady flow is shown. It seems to be valid that higher combustion temperature, complex flame structure and existence of char layer in CTPB bring less terminal velocity and higher drag coefficient than those of PU spheres having the same size. In addition, the drag coefficients of CTPB sphere were several times as high as, and those of PU nearly equal to or a little as low as corresponding burning hydrocarbon droplets, and both of burning polymer spheres yielded several times as large drag coefficients as non-burning standard solid spheres.[1]

In hybrid motors the atomized oxidizer stream will produce the break-up of liquid layer on the slab surface of fuel polymer, and it is more likely to result in the secondary formation of fragmented droplets by aerodynamic drag force. Even at the beginning of burning, the disintegration of combustible liquid layer and char layer will produce dusts and small ligaments like smoke. In the design of combustors, it is an important problem to suppress the performance deterioration due to multi-phase flow occured as the result that the surface of polymer fuel is torn into fine segments.

Reference

(1) C.T. Crowe, J.A. Nicholls and R.B. Morrison; 9th Symposium (International) on Combustion, Academic Press Inco., London, New York (1963), p. 395.

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