BURNING OF MAGNESIUM PARTICLES
IN WATER VAPOR

V. P. Prachukho, E. S. Ozerov,
and A. A. Yurinov

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In the large number of articles on the investigation of the burning of magnesium in oxygen there are practically no data on the burning of this metal in a medium of water vapor. The latter case is interesting in that free hydrogen is inevitably formed in the burning zone, the content of which affects the conditions of transfer of heat and reagents near the particle. If we take into account that the coefficient of diffusion of an oxidizing agent in hydrogen is almost an order greater than in nitrogen or argon, we can expect that the presence of hydrogen will lead to an increase of the rate of supply of the oxidizing agent. However, the specific heat of combustion of metal in water vapor is less than in oxygen, and therefore the burning rate, depending on the temperature gradient near the surface of the particle, can also decrease in water vapor.

Data on the effect of pressure on the medium on the burning rate are essential from the viewpoint of the mechanism of burning. As is known [1], for aluminum the burning rate increases with pressure, contrary to the conclusions of the quasistationary [2] and nonstationary [3] diffusion theories of burning. Taking into account the different mechanism of burning of magnesium and aluminum in oxygen [4], we cannot even qualitatively predict the character of the pressure dependence for the burning rate of magnesium.

The problems indicated below are discussed on the basis of the data of an experimental investigation of the burning of magnesium in mixtures of water vapor with nitrogen at pressures greater than or equal to normal.

1. The device was mounted on cover 1 of a bomb and inserted into the latter from the top so that the viewing slit 4 in the ceramic working channel 3 was placed opposite the longitudinal viewing window of the bomb. The cover 1 was fastened on the bomb by a sleeve nut, and sealing was accomplished by means of rubber gasket 2. The bomb itself was a cylindrical steel vessel with an inside diameter of 100 mm and height of 50 mm (Fig. 1).

To create a high-temperature flow of water vapor we used a flat-flame oxygen-hydrogen burner 5 to which were delivered through two collector half-rings the components of the fuel mixture: hydrogen and oxygen in a mixture with nitrogen. These components then emerged from the burner along narrow staggered channels, mixed, and burned near the mouth of the burner within a zone not more than 5 mm thick. Since the burning zone was located quite close to the burner, the latter was cooled by flowing water. The high-temperature gas flow from the burner was directed upward along ceramic channel 3 with an inside diameter of 18 mm and length of 250 mm.

The magnesium particle was delivered to the flow from below through a central hole in the body of the burner by means of vibrating feeder 6 [5]. The feeder made possible separate delivery of single magnesium particles at a given frequency.

All components of the fuel mixture, air to the feeder, and the water for cooling the burner were delivered through branch pipes welded into the cover of the bomb (see Fig. 1). The combustion products escaped through a similar branch pipe.

TABLE 1

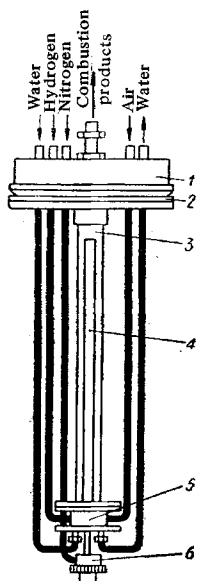| No. of fraction	Particle size, μm		
	minimum	maximum	average
1	22	40	34
2	37	64	55
3	66	116	90
4	86	133	117
5	102	152	139
6	144	205	184

Fig. 1

The composition of the mixture and all flow rates of the gases were measured by precalibrated measuring plates. The pressure in the bomb was established and kept constant by means of a discharge valve. A membrane manometer was used for measuring the pressure. The gas temperature was measured by W-Re and Pt-Pt/Rh thermocouples.

The fuel mixture was ignited by a spark discharge between two 1-mm-diameter nichrome wire electrodes built into the wall of the ceramic channel 3 near the mouth of the burner. The high voltage for the discharge was created by means of a Ruhmkorff coil.

The burning particles were recorded on a continuously moving 35-mm photographic film. The speed of the film was usually 0.5 m/sec.

A rotating disk shutter was located in front of the objective of the recorder during photography. Thus, the track of the burning particle on the film was discontinuous, and knowing the frequency of rotation of the shutter, we could determine the time of burning of the particle.

As the test material we used magnesium powder consisting of spherical particles with a diameter of 1-250 μm. We separated six fractions of particles from the original powder. Each fraction was characterized by an average size, which was determined as the arithmetic mean for a sample of 300-400 particles.

We indicate that for all fractions the root-mean-square size differed from the arithmetic mean by no more than 8%.

Table 1 gives the characteristics of all six fractions, the minimum and maximum being the sizes corresponding to the values of distribution functions 0.05 and 0.95, respectively.

After the test fraction was consumed under given conditions, we calculated the burning time of each particle from the tracks obtained on the film. As a result of processing 300-400 tracks we determined the average burning time, which was assigned to the average size of the test fraction. However, this comparison is permissible only if all particles of a given fraction ignite and burn up.

To check the completeness of combustion we carried out experiments in which powders with a maximum particle size less than the minimum size in the test fraction and with a minimum size greater than the maximum size of the particles of the same fraction were consumed. If particles of such powders were ignited, it was considered that the particles of all sizes in the test fraction also ignite under the given conditions. In addition, during the experiment we collected the combustion products on microscope slides and made a qualitative chemical analysis of them to find unburned particles.

The values of the burning time given below were obtained in those cases when the remains of the burned particles represented oxides and did not contain metal.

2. To investigate the pressure dependence of the burning time of a magnesium particle, experiments were carried out for fractions with average particle sizes of 55 and 90 μm. Both fractions were burned in a medium containing 0.35 water vapor and 0.65 nitrogen (the concentrations are given in mole fractions). The temperature of the medium in this case was 1050-1150°C. As a result we obtained the dependences presented graphically in Fig. 2. Curve 1 in this figure corresponds to the largest fraction. We see that the burning time increases considerably with increase of pressure from 1 to 6 abs. atm and scarcely changes with a further increase of pressure.

Although the result obtained agrees qualitatively with the conclusion of Spalding's nonstationary diffusion theory [3], it is necessary to bear in mind a number of characteristics of the process when interpreting the experimental data. First of all, this is the presence of homogeneous and heterogeneous condensation of oxide vapors with a different phase state of the oxide on the particle surface (liquid oxide for aluminum and solid oxide for magnesium). At normal pressure these characteristics result, for example, in the
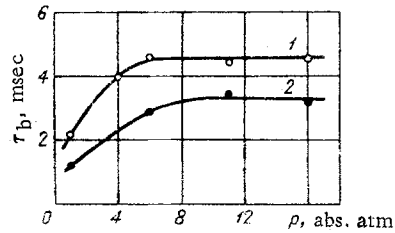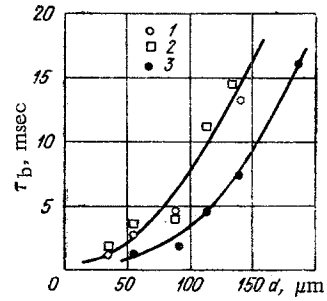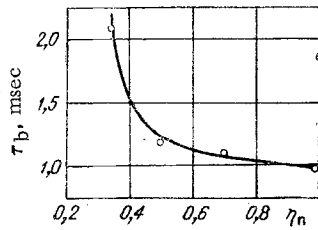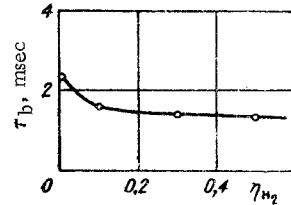
Fig. 2

Fig. 3

Fig. 4

Fig. 5

burning time of aluminum in oxygen being proportional to size in a power less than 2 (~1.5), and for magnesium particles greater than 2 (~2.5) [4].

Figure 3 gives the dependences of the burning time on particle size at pressures of 11 (1), 6 (2), and 1 (3) abs. atm (35% H_2O, 65% N_2). At normal pressure the curve is approximated satisfactorily by the dependence

$$\tau_b = 2 \cdot 10^{-5} d^{2.6}, \tag{1}$$

and at pressures of 6 and 11 abs. atm by the dependence

$$\tau_b = 4.8 \cdot 10^{-3} d^{1.6}. \tag{2}$$

In formulas (1) and (2) the burning time is obtained in milliseconds if the particle diameter is taken in microns. A change of the character of the dependence with increase of pressure indicates a change of the mechanism of burning mainly in the pressure region from 1 to 6 abs. atm.

To determine the dependence of burning time on concentration of water vapor, we conducted a series of experiments at normal pressure. Fractions with an average size of 90 μm were tested. The concentration of water vapor was varied from 0.35 to 1.0. The dependence obtained is presented in Fig. 4.

We need point out a characteristic of all results obtained in this study: the values of the Sreznevskii constant, which characterizes, as is known, the burning rate of a particle, were quite high. For example, for a 90-μm-diameter particle at normal pressure its value is equal to 4 mm^2/sec. Such a high value of this constant is possibly related with the specific character of the burning of magnesium in water vapor. As already mentioned above, in this case free hydrogen is formed in the burning zone, which can affect the process of heat and mass transfer in the region adjacent to the particle. Of interest in this connection is the result of the following experiment. Nitrogen, which was contained as an inert gas in a medium with a water vapor concentration of 0.35, was replaced by hydrogen so that the concentration of vapor in the medium remained unchanged. At normal pressure we measured the burning time of particles of fraction No. 3. We found that even an insignificant content of excess hydrogen in the medium causes a noticeable decrease of the burning time of the particle (Fig. 5).

The qualitative observations of the burning of magnesium particles are of interest. If excess hydrogen was absent in the medium, the tracks were always long, wide, and distinct. On adding hydrogen the tracks became narrower and shorter, and a wide luminous halo formed around the burning particle. We can assume that in this case the burning zone approached the particle surface, as a consequence of which the rate of vaporization of the metal increased.

A similar picture was observed also in the case of burning of magnesium particles in media rich with water vapor. True, in this case the temperature of the medium could also have had some effect on the burning rate. At a vapor concentration of 100% it reached 1800 as opposed to 1100°C for a 35% concentration.

We need note in conclusion that in all experiments burning of the magnesium particles was vapor-phase, the tracks were always very bright, white, and their width was double or triple the diameter of the burning particle. This is unconditionally explained by the fact that the temperature of the medium always exceeded considerably the maximum temperature of ignition of the magnesium particles of the investigated sizes.

The combustion products represented conglomerates of white magnesium oxide of varying size: from 5-10 to 40-50 μm. Sometimes these were hollow spherical shells exceeding the size of the initial particles by a factor of 2-2.5. These products did not contain metal (p = 1 abs. atm).

LITERATURE CITED

1. A. F. Belyaev, Yu. V. Frolov, and A. I. Korotkov, Fiz. Goreniya i Vzyrva, 4, 3 (1968).
2. G. F. Knorre, K. M. Aref'ev, et al., Theory of Furnace Processes [in Russian], Énergiya, Moscow-Leningrad (1966).
3. D. B. Spalding, VRT, 10 (1960).
4. M. A. Gurevich and E. S. Ozerov, Author's Abstract of Report at the Second All-Union Symposium on Burning and Detonation [in Russian], Chernogolovka (1969).
5. M. A. Gurevich, G. V. Ignatov, et al., Fiz. Goreniya i Vzryva, 5, 3 (1969).