Ignition and Combustion of Levitated Magnesium and Aluminium Particles in Carbon Dioxide

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Abstract

This article considers ignition and combustion of single particles of magnesium and aluminium in carbon dioxide at pressures 0.1-2 MPa. An experimental set-up with an electrodynamic levitator inside a high-pressure chamber was employed. The CO_2-laser was used for heating to ignition of the particles. The results show that ignition mechanisms of Mg and Al in CO_2 are different. Experiments with Mg indicate the existence of the critical partial pressure of CO_2, whereas the ignition probability of Al particles in CO_2 is low but independent on pressure. Analysis of flame images and combustion parameters shows that the mechanism of Mg particle burning in CO_2 corresponds to conventional models of vapour-phase diffusion-controlled combustion, whereas in the case of Al exothermic processes on the particle surface or close to it play a leading part in the burning process.

Introduction

Combustion of aluminium and magnesium in gaseous carbon dioxide is of interest for rocket engine applications. Current solid propellants normally contain metals as high energetic fuel, and the gaseous CO_2, along with H_2O, is often the main oxidising component for metal particles in a solid rocket motor. Aluminium is characterised by a higher heat of combustion than magnesium, and for this reason it is aluminium that is used in most of solid rocket motors. However, magnesium offers an important advantage over aluminium, namely, its ignites much easier than aluminium, especially in CO_2 containing atmospheres. In some cases this advantage may be the deciding argument in favour of magnesium. One example of a propulsion system where magnesium might be advantageous is a rocket engine for Mars missions using Martian CO_2 as an oxidiser [1]. It is therefore important to compare combustion characteristics and mechanisms of these metals.

In this paper we summarise and analyse the experimental results on ignition and combustion of single particles of magnesium and aluminium in carbon dioxide, which have been obtained with the *metal particle burning facility* of the LCSR.

Experimental set-up

The experimental set-up (Fig. 1) composes essentially of an electrodynamic levitator placed inside a high-pressure combustion chamber [2, 3]. Single charged particles are levitated inside the hermetic chamber and ignited with a CO_2-laser. The laser is automatically switched off after ignition. Photomultipliers and high-speed cinematography are used to obtain information on the ignition and combustion processes. The experiments reported here were conducted with the oxidiser at room temperature over the range of pressures from 0.1 to 2 MPa.

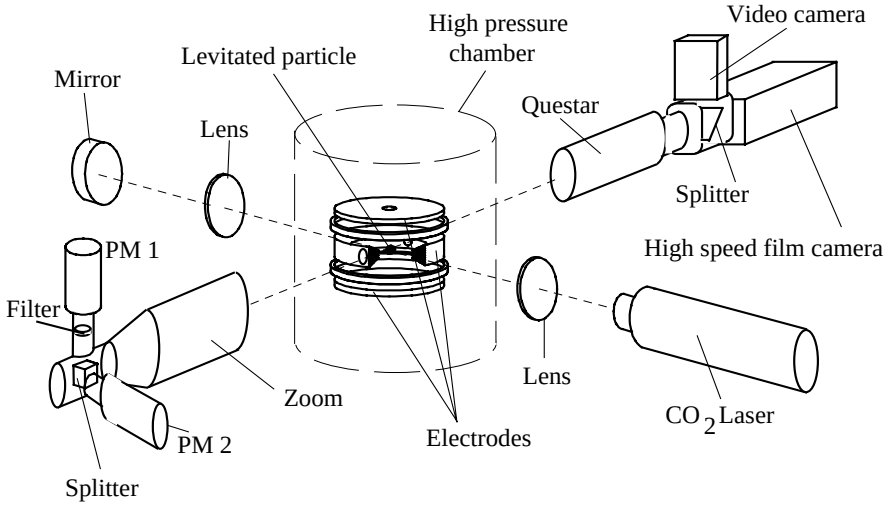

Figure 1 *Schematic of the experimental set-up*

Results and discussion

Critical conditions of ignition

The experiments show that levitated Mg particles ignite in CO_2 and CO_2/Ar mixtures if the partial pressure of CO_2 in the atmosphere exceeds some critical value. The critical pressure of ignition increases with decreasing the particle size, that is explained by increasing the heat-loss rate. The dependence of the ignition probability on the partial pressure of CO_2 (Fig. 2) implies that ignition of Mg particles in CO_2 is controlled by chemical kinetics.

In contrast to Mg, the experiments on ignition of Al particles in CO_2 do not indicate the existence of the critical pressure of ignition. The ignition probability is more than zero but less than 50 % over the range of tested pressure from 0.1 to 2 MPa. The observed difference in critical conditions for Al and Mg may be associated with the high protective properties of oxide films on the surfaces of Al particles.

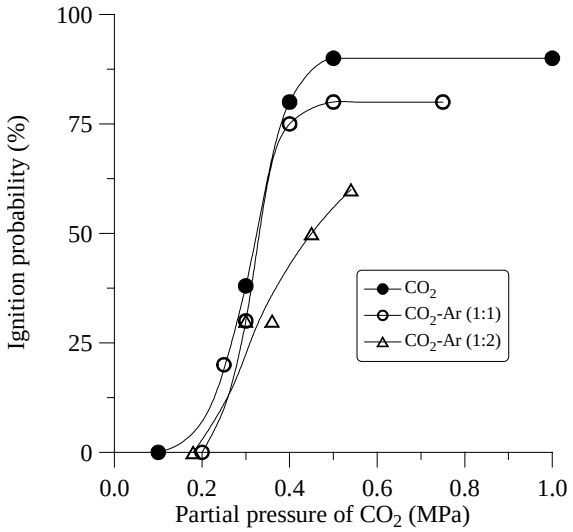

Figure 2 *Ignition probability of spherical Mg particles (50-63 µm) in different CO_2 - Ar mixtures versus partial pressure of CO_2*

Flame structure

Combustion of Mg and Al particles in CO_2 is accompanied with formation of a spherical vapour-phase flame, the brightness of which increases with increasing pressure. The great oscillations of the flame luminosity are inherent to combustion of Mg in CO_2, whereas the luminosity of Al flame gradually decreases during combustion. Local break-ups of symmetry and fragmentation at the end of burning are observed during combustion of both Mg and Al in CO_2. These phenomena are apparently associated with accumulation of combustion products on the particle surface and cannot be described by the existent mathematical models.

Analysis of flame images shows that structures of Mg and Al flames are quite different (Figs. 3 and 4). The structure of Mg flame in CO_2 corresponds to the conventional models of vapour-phase burning, which predict the temperature maximum some distance from the particle surface. On the contrary, the brightness of Al flame in CO_2 decreases monotonously from the particle surface to the surroundings.

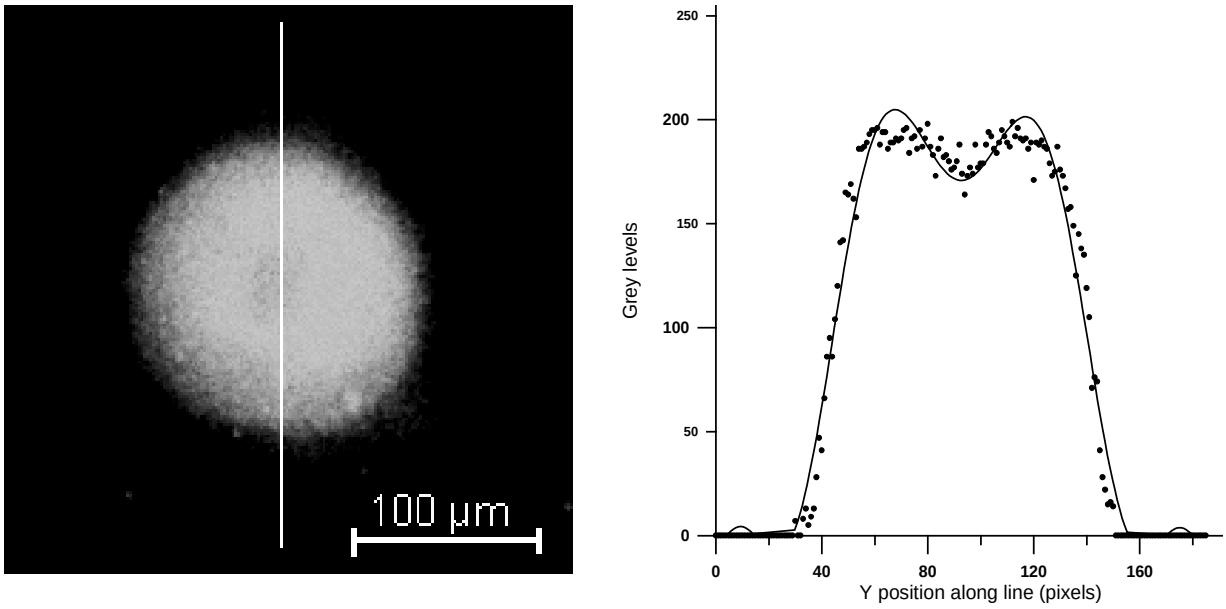

Figure 3 *Image of a Mg particle (~60 µm) burning in CO_2 and brightness of the image along the vertical line*

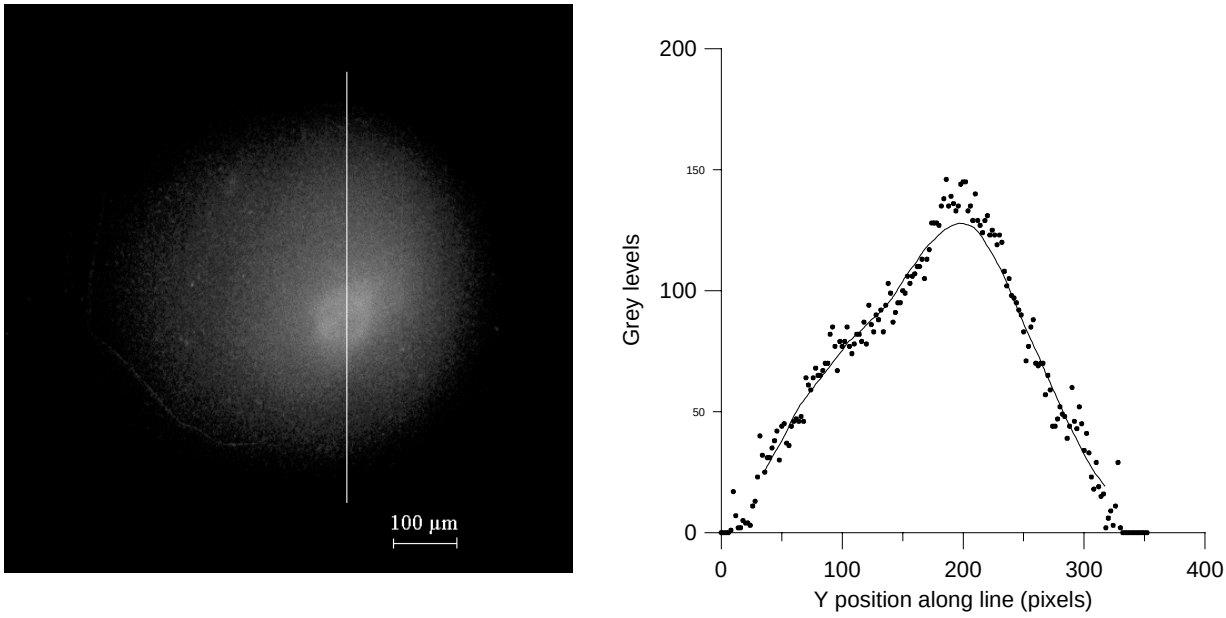

Figure 4 *Image of an Al particle (~60 µm) burning in CO_2 and brightness of the image along the vertical line*

Thermodynamic calculations show that the maximum adiabatic flame temperatures of Mg and Al in CO_2 are close to each other, whereas the boiling point of Al is much higher than that of Mg and is equal approximately to the maximum adiabatic flame temperature of Al in CO_2 in the considered range of pressure 0.1-2 MPa. Consequently, in the case of Al particle burning in CO_2, the temperature maximum is either on the particle surface or in gas phase very close to the surface, that corresponds well to the images obtained.

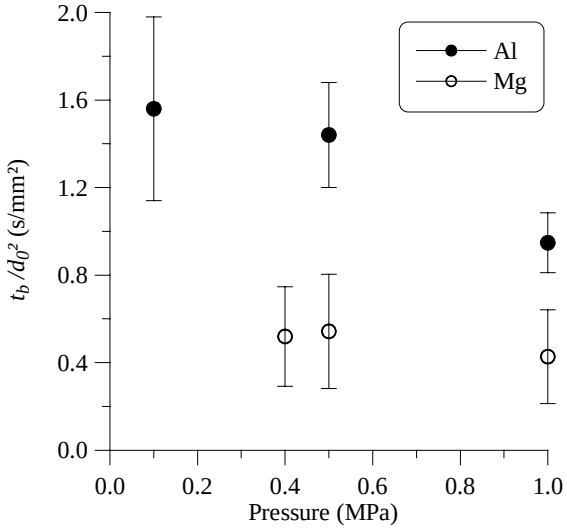

Figure 5 *Effect of pressure on the inverse burning rate of Mg and Al particles in CO_2 (t_b is the burning time, d_o is the initial size)*

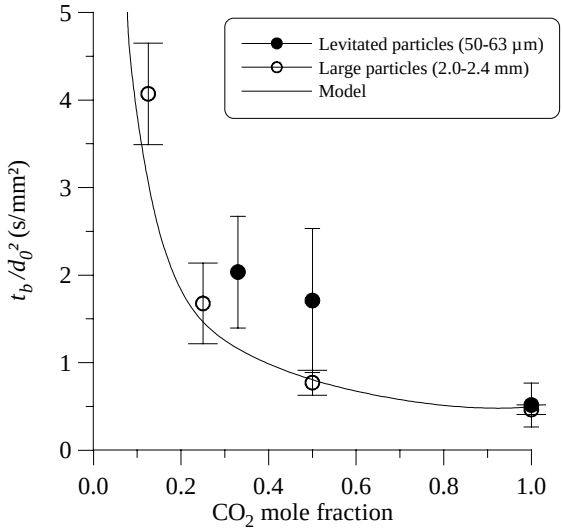

Figure 6 *Comparison of measured burning times of levitated Mg particles in CO_2 and CO_2/Ar mixtures with data for large particles [4] and with predictions by model [5]*

Burning rate

The burning rate of levitated Mg particles in CO_2 practically does not depend on pressure (Fig. 5). Comparison with the previous results on combustion of large Mg particles in CO_2 [4] shows that the exponent in the power-law dependence of the burning time of Mg particles in CO_2 on the initial particle size is equal to 2.0 over the range of sizes from 50 µm to 2.5 mm. The burning time of levitated Mg particles in CO_2 increases significantly with decreasing CO_2 mole fraction in CO_2/Ar mixtures. The burning time measurements of levitated Mg particles in CO_2 and CO_2/Ar mixtures (Fig. 6) correlate well with the results of experiments with large particles [4] and with the predictions by a quasi-steady model of diffusion-controlled vapour-phase burning [5].

The burning time of levitated Al particles in CO_2 decreases with increasing pressure (Fig. 5). The different structures of Mg and Al flames as well as the different effects of pressure on the burning rate imply that the combustion mechanism of small Al particles in CO_2 differs from that of Mg particles and cannot be described by conventional models of diffusion-controlled vapour-phase burning. In particular, the exothermic processes on the particle surface or close to it play a leading part in the combustion of small Al particles in CO_2, which is possibly the kinetics-controlled process.

References

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