NICKEL-COATED ALUMINUM PARTICLES: A PROMISING FUEL FOR MARS MISSIONS

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Combustion of metals in carbon dioxide is a promising source of energy for propulsion on Mars. This approach is based on the ability of some metals (e.g. Mg, Al) to burn in CO_2 atmosphere and suggests use of the Martian carbon dioxide as an oxidizer in jet or rocket engines [1, 2]. Analysis shows that CO_2/metal propulsion will reduce significantly the mass of propellant transported from Earth for long-range mobility on Mars and sample return missions. Recent calculations for the near-term missions indicate that a 200-kg ballistic hopper with CO_2/metal rocket engines and a CO_2 acquisition unit can perform 10-15 flights on Mars with the total range of 10-15 km, i.e. fulfill the exploration program typically assigned for a rover [3].

Magnesium is currently recognized as a candidate fuel for such engines owing to easy ignition and fast burning in CO_2 [1, 2, 4]. Aluminum may be more advantageous if a method for reducing its ignition temperature is found. Coating it by nickel is one such method. It is known that a thin nickel layer of nickel on the surface of aluminum particles can prevent their agglomeration and simultaneously facilitate their ignition, thus increasing the efficiency of aluminized propellants [5, 6].

Combustion of single Ni-coated Al particles in different gas environments (O_2, CO_2, air) was studied using electrodynamic levitation and laser ignition [7]. It was shown that the combustion mechanisms depend on the ambient atmosphere. Combustion in CO_2 (see Fig. 1) is characterized by the smaller size and lower brightness of flame than in O_2, and by phenomena such as micro-flashes and fragment ejection (see image 4). The size and brightness of flame gradually decrease as the particle burns.

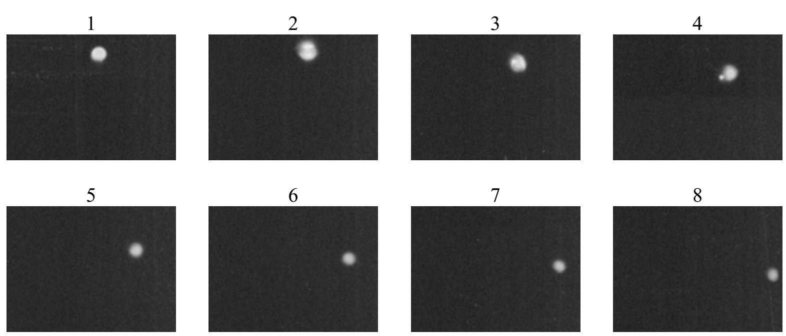

Figure 1: Combustion of Ni-clad Al particle in CO_2.
(0.5 μs between images, viewing area 1236 x 921 μm)

Remarkably, burning of Ni-clad Al particles in air (see Fig. 2) involves two stages, with inverse images of flame (bright core-dark flame and dark core-bright flame). Such images have never been observed in prior experiments with pure Al particles. Thus, we expect that this new phenomenon is caused by the presence of two elements (Al and Ni) in the particles.

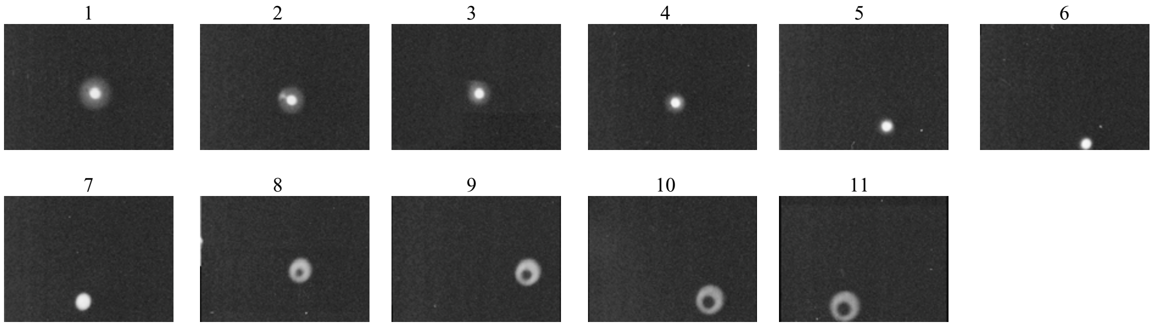

Figure 2: Combustion of Ni-clad Al particle in air.
(1.3 μs between images, viewing area 1236 x 921 μm)

Recent studies [8] show that the Ni coating dramatically decreases both the ignition delay time of laser-heated Al particles and the critical ignition temperature of gas-heated Al particles. Exothermic intermetallic reactions between liquid Al and solid Ni are considered as the main reason for the lowered ignition temperature of Ni-coated Al particles.

The detailed characterization of the process requires spatial and temporal resolutions that can be achieved only with relatively larger particles (1-5 mm). To avoid the natural convection and liquid flow effects, experiments on combustion of such particles will be conducted in microgravity environment using NASA research aircraft. The ignition and combustion will be studied by using high-speed and infra-red video cameras, and product composition analysis. Special attention will be devoted to elucidating the roles of inter-metal reaction and physical processes in surface layers (e.g. cracking of the shell, melt spreading).

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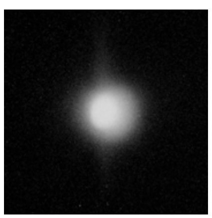
NASA Office of Biological and Physical Research
Strategic Research to Enable NASA's Exploration Missions

Combustion of metals in CO_2 as an alternative approach in Mars in-situ resource utilization

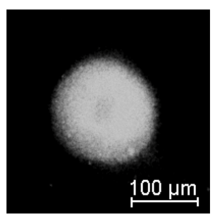
- Typical approach in Mars ISRU: ***To produce rocket propellants from Martian CO_2*** (95% of Mars atmosphere). Problems: high power and chemical processing on Mars are required.
- Alternative approach: ***To use Martian CO_2 directly as an oxidizer in a rocket engine*** [1]. Based on combustibility of metals in CO_2 and easy liquefaction of CO_2 under Martian conditions (pressure 8 mba, typical average temperature 230 K in middle latitudes).

Combustion of Mg and Al particles in CO_2

Al, 50 μm [2]

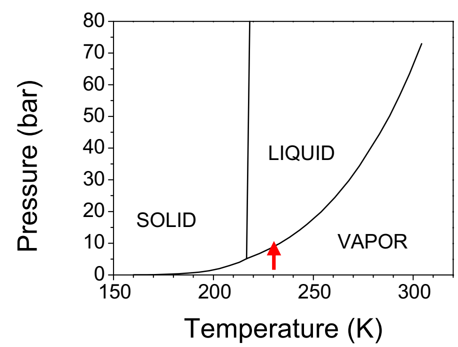


Mg, 50 μm [2]



Mg, 2 mm, microgravity [3]

CO_2 Phase Diagram



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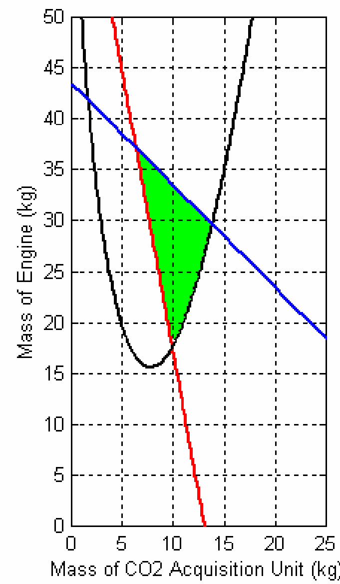
Advantages of metal-CO_2 propulsion in Mars missions

- Reduced mass of propellant transported from Earth for ***long-range mobility on Mars***. Several ballistic flights are possible (CO_2 is acquired before every takeoff).
- Only CO_2 acquisition but ***no chemical processing on Mars***.

Missions: hopper, multi-sample return.

Design domain for hopper [4]
Hopper mass = 200 kg, power = 300 W
Propellant: Martian CO_2 and Mg from Earth
Scenario: 10 hops, total range = 10 km,
mission duration = 180 Martian days
Conclusion: Mission is possible.



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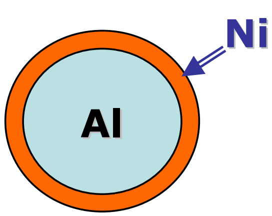
Problems in metal-CO_2 propulsion and how to fix them

- ***Low specific impulse*** of Mg-CO_2 rocket, ~200 s
  (though still advantageous because the oxidizer is present on Mars!)

- ***High ignition temperature*** of Al particles in CO_2, >2000 K
  (the ignition temperature of Mg in CO_2 is about 1000 K)

Al will be the best fuel choice if a method is found to reduce the ignition temperature of Al particles. ***Coating by nickel*** is one such method. It is expected that intermetallic reactions of Ni and Al trigger ignition and significantly reduce the ignition temperature [5].

Typical dimensions of Ni-coated Al particles:
Al core diameter: 10 - 100 μm
Ni layer thickness: 0.01 - 1 μm



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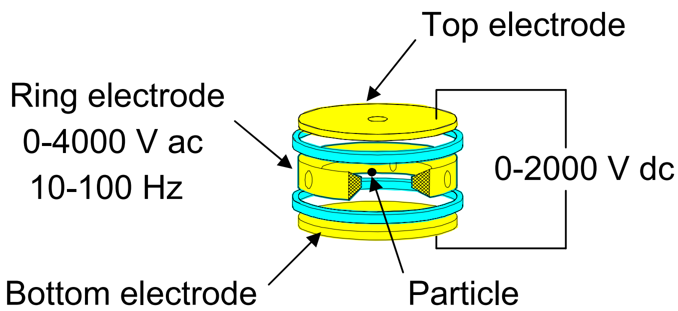
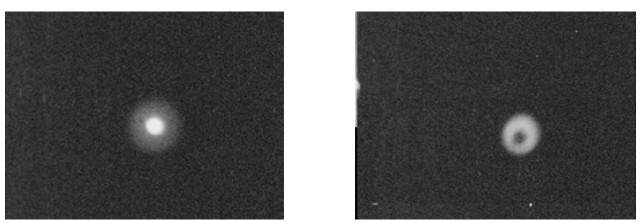
Ignition and combustion of single Ni-coated Al particles

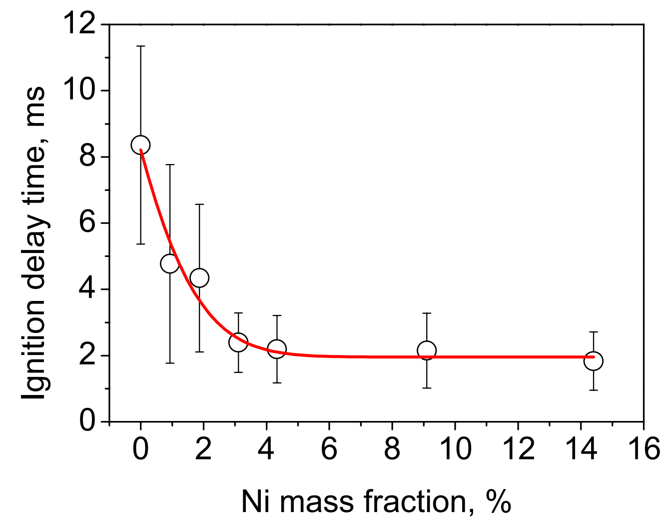
Method: electrodynamic levitation



Two-phase burning in air [5]



Ignition in air [6]



Ni coating dramatically decreases both the ignition delay time and the ignition temperature of Al particles (~1000 K *vs.* >2000 K for non-coated Al)

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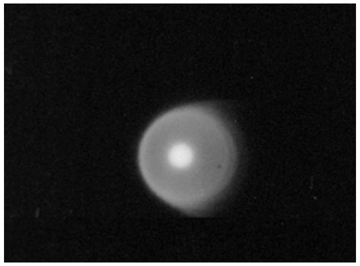
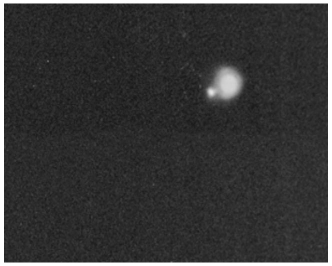
Ignition and combustion of single Ni-coated Al particles (continued)

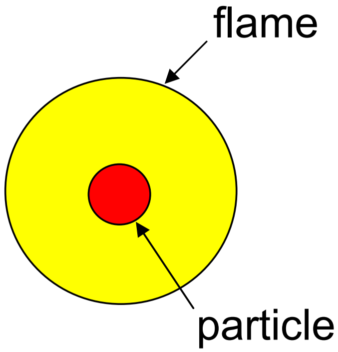
Combustion in O_2 and CO_2 [5]

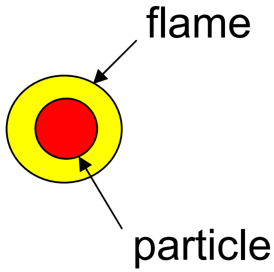
Atmosphere: O_2
T_{ad} ~ 4000 K



Atmosphere: CO_2
T_{ad} ~ 3200 K







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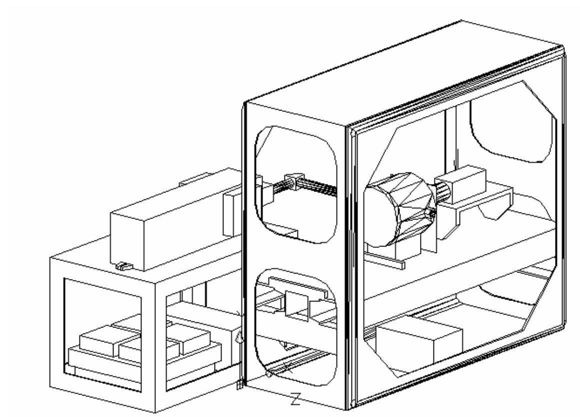
Combustion of complex metal particles in microgravity

(NASA Grant NNC04AA36A, started Jan. 1, 2004)

The detailed characterization of the ignition/combustion process requires spatial and temporal resolutions that can be achieved only with particle size 1-5 mm. To avoid the natural convection and liquid flow effects, experiments on combustion of large Ni-coated Al particles will be conducted in microgravity environment using NASA research aircraft. The particles will be installed on thin wires inside a reaction chamber and ignited by a CO_2-laser. Combustion in different gases will be studied.

Schematic diagram of the experimental setup (design in progress)



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What should NASA undertake to make the metal-CO_2 propulsion on Mars a reality?

To organize/support

- Fundamental studies on combustion of metals in CO_2
  Goal: *to identify/develop the best fuel for burning with CO_2 on Mars*
- Development of the liquid CO_2 acquisition system
  Goal: *to develop a reliable and efficient CO_2 acquisition system for operation on Mars*
- Development of the metal/CO_2 engine prototype
  Goal: *to prove that the metal/CO_2 engine can operate smoothly with high performance characteristics*
- Studies of metals recovery from Martian soil or lander used parts
  Goal: *to develop the method for production of metal fuel on Mars with sufficiently low power consumption*

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