METAL-CO_2 PROPULSION FOR MARS MISSIONS: CURRENT STATUS AND OPPORTUNITIES.

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Introduction: Mars ISRU plans usually involve production of liquid propellant components (e.g. O_2, CO, CH_4) on the planet surface. The common problem in these scenarios is the significant power required to produce, liquefy, and store cryogenic propellants. An alternative approach in the Mars ISRU, reviewed in this presentation, suggests using the Martian CO_2 directly as an oxidizer in a jet [1-4] or rocket [5-13] engine. This approach is based on the unique ability of some metals to burn with CO_2, briefly discussed below.

Combustion of Metals in CO_2: Reactions of metals with CO_2 have been present in propulsion and pyrotechnics for many years. For example, in solid rocket engines, Al particles burn in gaseous products of ammonium perchlorate/hydrocarbon binder combustion, where CO_2 and H_2O are the main oxidizers. The solid rocket applications and the idea of metal/CO_2 propulsion on Mars and Venus inspired researchers to study combustion of Al and Mg in CO_2, experimentally [14-41] and theoretically [25, 37, 42-45]. The fundamental studies show that both Mg and Al particles rapidly burn in CO_2 environment producing metal oxide, CO and relatively small amount of carbon. There is, however, a significant difference in ignition of Mg and Al, important for applications. Magnesium ignites in CO_2 at temperatures slightly above its melting point (933 K) whereas aluminum must be heated to near the melting point of Al_2O_3 (2327 K). Ignition of Al particles can be improved by additives and coatings. For example, Ni coating decreases the ignition temperature of Al particles by ~1000 K [46-48]. Analysis of the above-referred literature shows that significant knowledge and a high level of understanding have been reached for combustion of single Mg and Al particles in CO_2.

Types of Metal-CO_2 Propulsion: Performance characteristics of jet engines in CO_2 atmosphere of Mars were calculated for Al, AlH_3, H_2 [1], and Mg [2, 4] as fuel. Unfortunately, low atmospheric pressure on Mars leads to either low thrust [1], or large specific fuel consumption and extremely large inlet and exhaust nozzle [2]. In addition, stable operation of the metal-CO_2 turbojet is doubtful due to deposition of solid combustion products on the turbine blades [3] while ramjets require supersonic speeds of vehicle and hence cannot be used for takeoff from the Martian surface.

In [5], a rocket engine using liquefied CO_2 as an oxidizer and metals as fuel was proposed for Mars ascent vehicles. Thermodynamic calculations of the engine performance characteristics were made for various candidate metals, their hydrides and mixtures with hydrogen-containing compounds [5, 8]. The results indicate that the highest theoretical specific impulse (I_{sp}) could be reached with Be or BeH_2, while Mg and Al show the best results among other, non-toxic metals. Boranes proposed in [7] were excluded from further consideration due to high condensed phase fractions in the combustion products and expected boron oxide deposition in nozzles [8]. On the contrary, Mg and Al show relatively low fractions of condensed phase in combustion products, and their oxides have high melting points (3100 and 2327 K, respectively), which is a favorable fact to avoid agglomeration and deposition. Replacement of pure Mg or Al by a hydride of the metal increases the maximum I_{sp} but does not effect (for Al) or decreases (for Mg) I_{sp} at oxidizer/fuel ratios higher than stoichiometric. The thermodynamic calculations, analysis of properties and available ignition/combustion characteristics of metals support the conclusion that Mg is the main candidate fuel for rocket engine using CO_2. Aluminum can also be used provided its ignition is improved.

Production of Liquid CO_2 and Metal Fuel on Mars: Temperature and pressure on Mars surface create favorable conditions for liquefaction of CO_2 from the atmosphere. For example, Lockheed Martin's method collects pure CO_2 as a solid mass on a chilled surface and then produces high pressure liquid CO_2 by allowing the frozen mass to thaw [49]. For the metal fuel, two options are possible. The easier option is to transport the metal fuel from Earth to Mars. In this case, the in-situ propellant production system (ISPPS) is reduced to the CO_2 acquisition system, decreasing both power consumption and mass of ISPPS by about 80% [7]. The second option is to produce the metal fuel on Mars. One possibility is to recycle metal parts of lander or other materials that are no longer needed. Note that transforming structural aluminum to powdered fuel for H_2/O_2/Al rocket engines was discussed for recycling the Space Shuttle external tank on the orbit [50]. Another possibility is to recover the metal fuel from the Martian ores or soils. The content of Mg in Martian regolith is estimated to be 3.6%, against 0.5% in terrestrial soil [51]. There exists voluminous literature on methods for extraction of metals from lunar and Martian soils. Dissolving the regolith in supercritical CO_2 [52] is particularly attractive as it in-

volves liquid CO_2, obtained in large amounts anyway during production of the engine oxidizer.

Design of Metal-CO_2 Rocket Engine: Among different design options for the metal/CO_2 rocket propulsion system [5, 9, 10], direct feeding of the metal powder and the use of gelled CO_2/metal propellant are of particular interest. The direct powder feeding option involves a combination of a piston-cylinder assembly and a carrier gas, developed for engines and reactors using powdered metal fuel [4, 12, 53-55]. Vaporized CO_2 or an additional gaseous component, such as H_2 or N_2, can be used as the carrier gas. Note that to use CO_2 as carrier seems preferable because the use of additional component reduces the in-situ fraction of propellant. Additional liquid CO_2 can be fed as a conventional liquid propellant. In the case of gelled CO_2/metal propellant design, the feed system becomes even simpler, while still retaining the possibility to easily throttle and restart the engine. Although additional propellant processing operations on Mars are required, this design deserves further investigation. Experience in studies of metallized gelled propellants containing Al, kerosene, liquid O_2 and H_2 [56, 57] can be used for development of gelled CO_2/metal propellants.

Potential Missions Using Metal-CO_2 Propulsion: The reduction of propellant mass transported from Earth makes the metal/CO_2 rocket engine advantageous even despite the relatively low I_{sp} (~200 s for Mg or Al as fuel). It should be noted that I_{sp} can be increased by addition of hydrogen [3] but the H_2 storage is a significant problem. The term used sometimes in ISRU "effective I_{sp}", which is the thrust per pound of propellant transported from Earth, is higher by several times than the "normal" I_{sp} in missions with Martian CO_2 and Earth-born metal fuel, and tends to infinity when all propellant is produced on Mars. More careful analyses for "Martian CO_2 - Earth-born metal fuel" demonstrated that the proposed rocket propulsion system could be used as the first stage of the ascent vehicle in a mission with a single takeoff to Earth or to low Mars orbit [6, 12]. Significant advantages of metal/CO_2 propulsion are expected in missions with several ballistic flights (hops) on Mars, when the oxidizer (liquid CO_2) is taken from the atmosphere prior to each hop [5, 6, 10]. The most applicable analysis was made recently for a small (200 kg) hopper mission where CO_2 acquisition and required power were taken into account [13]. The obtained results show that the proposed hopper is competitive with a rover, while offering the benefit of terrain independence.

Thus, the rocket propulsion system using liquefied Martian CO_2 and Earth-born metal fuel could be advantageous in forthcoming robotic missions while the production of both CO_2 and metal fuel on Mars could play a significant role in more advanced, including human, missions.

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Journal Abbreviations: *CESW: Combustion, Explosion, Shock Waves; CF: Combustion and Flame; CST: Combustion Science and Technology; JBIS: Journal of the British Interplanetary Society; JPP: Journal of Propulsion and Power; PCI: Proceeding of the Combustion Institute.*