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A hybrid plasma technology life support system for the generation of oxygen on Mars: Considerations on materials and geometry

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ABSTRACT

As there is a growing interest in conducting human missions to Mars, the need for suitable life support systems becomes more and more important. The reliability of such systems has to increase with the duration of manned missions. Furthermore the maintenance requirements have to be low in order to ensure their efficient use over a long period of time. A proposal for a hybrid life support system that is based on plasma technology for the creation of oxygen from the dissociation of carbon dioxide is given in this paper. The main focus lies on geometrical considerations regarding the optimal shape of the main reactor chamber as well as on suitable materials, which are most promising for the construction of such a system.

1. Introduction

In recent times longer sojourns in space have become more and more common and the number of plans for manned missions to Mars is steadily increasing. This urges the need for reliable life support systems for the production of oxygen as well as the recycling of used breathing air on space vessels and potential Mars habitats. This paper is focused on the latter one, although the principles presented herein can also be applied for space stations or space vehicles. As the CO_2 is the main content of the Martian atmosphere there have already been proposals for utilizing it for life support systems [1] or the production of rocket fuels [2]. Most technologies for life support systems on Mars are based on photo- or electrochemical processes and microorganisms like cyanobacteria or algae [3,4]. However, it has also been demonstrated in previous work how the carbon dioxide in the Mars atmosphere can be utilized for creating oxygen by plasma assisted dissociation and can produce useful carbon based resources in the same process [5]. The basic concept of such a hybrid life support system shall be developed further in this paper with emphasis on geometrical consideration for the reactor shape and suggestions of possible materials for its construction that are suitable for space technology applications. Using plasma technology for improving the operation conditions of life supporting systems is not an entirely new concept. Plasma pyrolysis, for instance, was applied to increase the oxygen recovery rate from a Sabatier System [6]. This work, however, is devoted to a plasma reactor that dissociates CO_2 into carbon and oxygen and separates the breathable oxygen via centrifugal forces. The manuscript is organized as follows: first the technical considerations, such as the geometry of the reactor and the separation rates for the gas species will be described and then the results will be summarized and discussed.

2. Technical considerations

The decomposition of carbon dioxide can occur in two different reaction channels: $CO_2 \rightarrow CO + \frac{1}{2}O_2$ (incomplete dissociation) and $CO_2 \rightarrow C(s) + O_2$ (complete dissociation). Usually both of these two reactions take place in plasma assisted dissociation of carbon dioxide. However, it has to be mentioned that the complete dissociation reaction usually starts with the reaction of incomplete dissociation, followed by a second step: $CO + CO \rightarrow CO_2 + C(s)$ [7]. Thus, for the sake of simplicity, only complete dissociation is used for the general considerations in this work. This does not influence the technological outcome or the basic principles as only the production of CO is neglected but the main end products (carbon and molecular oxygen) are still under consideration. After the plasma dissociation the products are immediately separated by centrifugal force. Hence the probability of CO and O forming CO_2 is very low. Additionally, recent experimental publications demonstrated the overall dissociation rate in different discharge types along with the energy efficiency listed in Table 1.

It has been demonstrated in [5] that the power consumption for the production of the average daily oxygen intake of a human (ca. 4 m^3 of O_2) is around 1.1 kW. If a well-tuned microwave or rf

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Table 1
Maximum dissociation rates and electric efficiencies of different plasma reactors and pressure ranges.

Discharge type	*p* (Pa)	Diss. rate (%)	Energy eff. (%)	Ref.
Microwave (2.45 GHz)	20–150	13.0	n.a.	[8]
Microwave (2.45 GHz)	2660	70.0	22.5	[9]
Microwave (2.45 GHz)	133–1333	80.0	12.0	[10]
rf (13.56 MHz)	20–2800	55.0	n.a.	[11]
rf (13.56) MHz	6–40	90.0	3.0	[12]

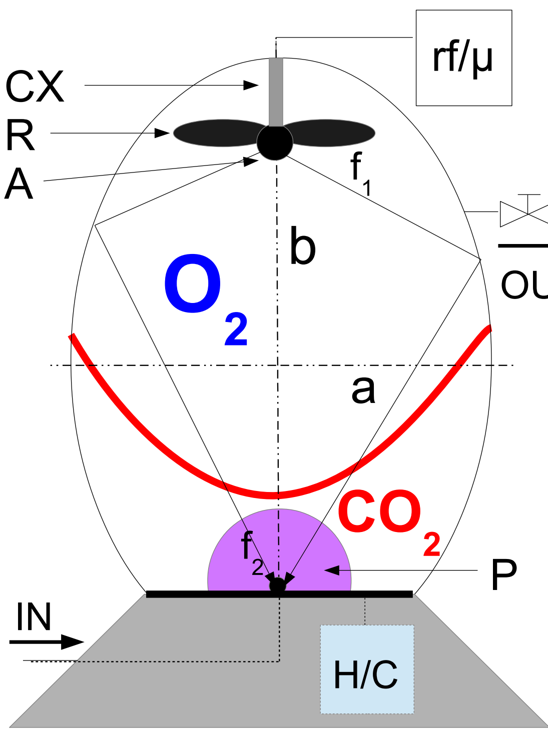

Fig. 1. Schematics of the hybrid plasma reactor. Abbreviations: a – semi-minor axis of the ellipse or radius of the vessel, b – semi-major axis of the ellipse, rf/μ – rf or microwave generator, CX – insulated coaxial antenna for the rf signal input, R – polymer rotor, A – rf antenna or microwave input, f – focus points of the ellipsoid, P – dense main plasma, IN – gas inlet, OUT – gas outlet with safety valve, H/C – optional substrate heating/cooling with temperature sensor.

plasma source, which is working under Mars-like pressure regimes (636 Pa at 240 K on average [13]), is considered for the CO_2 dissociation, one can expect an average dissociation rate of ca. 75% and an energy efficiency of around 20%, according to Table 1. This indicates a necessary input power of 5.5 kW is sufficient to produce the amount of oxygen needed by a human being. The volume per unit time of atmosphere that has to be processed in this fashion is then 1013 liters per minute for average Mars conditions [5]. In order to do that efficiently one can use a plasma reactor that is shaped like a rotation ellipsoid as depicted in Fig. 1.

The biggest advantage of such a shape is the fact that it has two focal points, which allow to create a spatially well defined plasma by locating the rf or microwave signal input at the first focal point. The in-coupled waves will then all be collimated at the second focal point where the energy density becomes highest. The main separation mechanism of carbon dioxide and oxygen is then achieved by centrifugal force, created by the fast turning rotor R, which forces the non-dissociated CO_2 to the reactor walls while the produced atomic carbon can be utilized to deposit useful carbon phases such as diamond, carbon nanotubes, carbon nanowalls, graphene, etc. For this purpose the substrate should be located at the plane of the second focal point and be equipped with a heating or cooling circuit and a temperature control as depicted in Fig. 1.

In a steady state operating condition the buoyancy force will also separate the two gases along the *z*-axis of the reactor, which creates the parabolic shaped CO_2 enriched region around the main plasma at the bottom of the reactor. The height as well as the curvature of this parabola is determined by the speed of the rotor. This also determines the optimal locus for the oxygen extraction pipe in the reactor wall. The best way to calculate the most advantageous position for this pipe can be calculated from the separation factor, which is usually used in gas centrifuge technology [14]:

$$\alpha_0 = \frac{x_1(0)}{x_2(0)} \cdot \left(\frac{x_1(a)}{x_2(a)}\right)^{-1} = \exp\left[(M_2 - M_1)\omega^2 a^2 \cdot \frac{1}{2RT}\right] \tag{1}$$

Here $x_{1,2}$ are the concentrations of the first and second gas species, a is the radius of the reactor, $M_{1,2}$ are the molecular weights of the gas particles (32 g/mol for O_2 and 44 g/mol for CO_2), ω is the angular frequency of the rotor, R is the ideal gas constant and T denotes the absolute temperature.

The calculated value for the radial dependency of the ratio between O_2 and CO_2 is depicted in the following Fig. 2 for different speeds of the rotor. It can readily be seen, that even for a comparably small speed of 200 rad/s the oxygen concentration drops significantly within a radius of 20 cm. This indicates that the minimum height at which the oxygen exhaust pipe has to be mounted is the height at which the wall of the plasma vessel is at least 20–5 cm away from the center axis of the reactor.

This decline becomes even more pronounced for higher rotational speeds up to 1700 rad/s, which corresponds to the rotational speed of a modern gas centrifuge of 10^5 rpm [15]. Furthermore it has been shown by Dirac that a gas centrifuge has a maximum output of [16]:

$$\delta U_{max} = \rho D \cdot \left(\frac{\Delta M \omega^2 a^2}{2RT}\right)^2 \cdot \frac{\pi Z}{2}. \tag{2}$$

Here ρ is the process gas density ($1.1 \cdot 10^{-2}$ kg/m^3 for a mixture of 75% O_2 and 25% CO_2 at average Mars conditions and calculated from the ideal gas law $\rho = \frac{p}{R_s T}$ with the specific gas constant R_s of 188.9 J/kg K for carbon dioxide and 259.8 J/kg K for oxygen), ΔM is the difference between the two molar masses, Z is the height of the reaction chamber ($Z = b + F$, where F is the distance between the focal point, given by: $F = \sqrt{b^2 - a^2}$, and the center of the chamber) and D is the diffusion coefficient, which can be calculated in (cm^2/s) from the Chapman–Enskog theory via [17]:

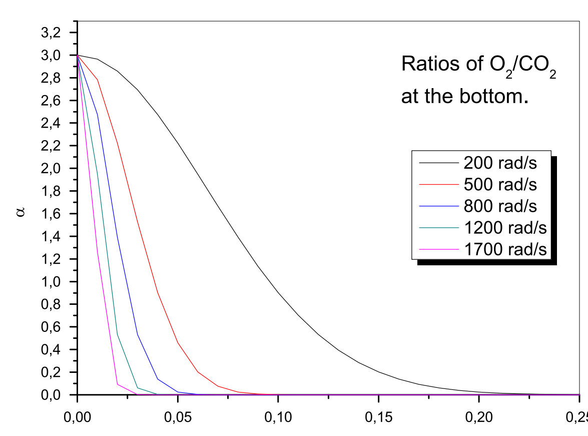

Fig. 2. Separation factor α for different rotational speeds.