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Mars transportation vehicle concept

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ABSTRACT

A concept of Mars planet propulsion vehicles is analyzed. Aluminum or magnesium combustion in CO_2 is considered as the main energy production cycle. The flight possibilities in rarefied Martian atmosphere are analyzed. The problem of lift force determination in compressible gas in the proximity of rigid surface was solved theoretically. It was demonstrated that lift force increase on approaching rigid surface could guarantee reliable flights in Martian atmosphere.

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1. Introduction

The forthcoming Mars exploration missions to be effective by covering maximal territory in course of one mission will need a reliable transportation vehicle. This brings the problem of local resource utilization on top of current research needs. The concept of Martian resources utilization for transportation enables technology for exploration of Mars, which can significantly reduce the mass, cost, and risk of robotic and human missions. The problem of rover versus hopper is to be solved. Both approaches have their advantages and disadvantages. In this paper we will concentrate on airborne propulsion. The critical element in future missions is the large mass of propellant for a Mars ascent vehicle, as well as power and propellant to accommodate a long stay and mobility on Mars. Transportation of propellant from Earth to Mars requires a great increase in the initial mass of hardware in low Earth orbit.

Most promising approach in the Martian resources utilization concept suggests using the Martian CO_2 directly as an oxidizer in a jet or rocket engine [1], because Martian atmosphere contains 95.3% carbon dioxide. This approach is based on the unique ability of some metals and compounds to burn with CO_2. The idea to burn metals in atmospheres of planets for propulsion appeared long ago. In early studies by Yuasa and Isoda [2], "CO_2-breathing" jet engines were considered. This looks advantageous, because no CO_2 processing is required and the propulsion system is the only element that needs to be developed in this case. For human missions, however, rocket engines are required. The low temperature of the Mars atmosphere favors CO_2 liquefaction, thus allowing relatively easy accumulation of liquid CO_2 at pressure 10 bar for subsequent use in rocket engines [1].

On the other hand, the low atmospheric pressure of Mars (7–9 mbar), being a major problem for jet engines, is perfect for rockets (no need for pressure higher than 10 bar in the combustion chamber to obtain high nozzle expansion ratio). These favorable circumstances were noted by Shafirovich et al. [3], who first conducted thermodynamic calculations of performance characteristics for rocket engines using metal-CO_2 propellants and made ballistic estimates. Then successful design solutions were developed for engines using powdered metal fuel with air or steam, which could be used in metal-CO_2

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propulsion systems. Fundamental studies of metals combustion have improved significantly understanding of Mg and Al particle combustion in CO_2 atmosphere. Progress was made in development of methods for liquid CO_2 production on Mars, and new ideas appeared for production of metal fuel on Mars. Finally, mission analyses have identified scenarios in which metal-CO_2 propulsion promises great advantages.

Performance characteristics of ramjet engines in the Martian (CO_2) atmosphere were calculated for use of magnesium [2] as fuel. Unfortunately, low atmospheric pressure on Mars leads to either low thrust, or large specific fuel consumption and large inlet and exhaust nozzle sizes [2]. Turbojet could be more efficient, but presence of oxide particles in exhaust gases could lead to particulate phase deposition and damaging the turbine blades. Pulse detonation engines [4,5] could be used much more successfully as they do not need turbines and provide higher specific impulse. However, periodical detonation onset becomes important [6]. Besides, using metal as fuel and CO_2 as an oxidant brings the problem of detonation onset and control in such a two-phase system.

The equilibrium calculation and experimental study on the ignition and combustion characteristics of magnesium, lithium, aluminum and boron in a CO_2 atmosphere suggest that magnesium is the most attractive fuel for the CO_2-breathing engine using in Mars atmosphere because of its easy ignitability and fairly fast burning rate [2], despite of the fact its specific energy release in CO_2 is twice less than in O_2 combustion, and 3–4 times less than hydrocarbon fuels burning in oxygen.

Another problem relevant to flights in Martian atmosphere is that of low density being approximately 60 times less than atmosphere on Earth, which means the Mars surface density is equal to atmospheric density on Earth at the altitude of 15 km. The lift force being directly proportional to atmospheric density provides much less favorable flight conditions. Combining this factor with lower thrust characteristics provided by metal burning in CO_2 engines, probably, brought the concept of rover dominating over hopper. The aim of the present paper is reconsidering traditional flight concept for Mars applications.

2. Aerodynamic screen effect

Making use of classical airplane flight concept in Martian atmosphere could be hardly realized due to atmospheric density being 60 times less than on Earth. The fact that gravity on Mars surface is only 38% of that on Earth does not compensate the difficulty, because for a typical air-plane weight being decreased 2.6 times the lift force should decrease 60 times for one and the same cruising velocity. The classical aerodynamics concept says that the lift force for subsonic wings is generated due to pressure differential on both sides of wing in streaming flow. The classical formulas for lift force of a single wing do not take into account the presence of other bodies in the flow. However, it is known that wing moving near rigid boundary produces strong effect on the forces acting on wing from streaming fluid [7].

At the beginning of the XX century it was observed that the lift force of a wing moving near flat surface increases strongly in comparison with free flight. An article about screen effect by Juriev [8] was published in 1923 in the USSR. That fact was used in creation of new flying devices – screen-planes, which got the Russian name “ekranoplan”. In 1932 Grohovsky constructed a full-scaled model of a new marine flying device – catamaran. At the same time Finnish engineer T. Kaario proceeded to test his flying apparatus that used a screen effect. Then (1963–1976) a Soviet machinery designer R.L. Bartini created a screen-plane project SVVP-2500 that took off in 1974. The first Soviet manned jet screen-plane SM-1 was created in collaboration with R. Alekseev in 1960–1961 [9]. Giant screen-plane KM was constructed by 1966 and “Orlyonok” type screen-planes were built from 1974 to 1983.[7] Designing of new flying devices continues in many countries.

Sedov obtained an analytical solution for the lift force in terms of Weierstrass functions [10] using theory of a complex variable. Approximate analytical solution of the problem of non-steady plane moving near rigid surface was obtained by Rozjdestvensky [11] using asymptotic expansion. Theoretical investigation of a wing moving near rigid surface was made by Panchenkov [12,13] and Gorelov [14], but the obtained solutions incorporated free constants. Experimental results are shown in [15]. Numerico-analytical solutions were obtained in [16]. Below numerical solution and analytical formulas for the wing flying near rigid surface will be obtained and analyzed for being applied in Martian flight vehicle design.

3. Mathematical problem statement

We regard plane wing motion in compressible ideal fluid. The system of equations for fluid flow in the motionless co-ordinates is the Euler system

$$\frac{\partial\rho}{\partial t}+V_x\frac{\partial\rho}{\partial x'}+V_y\frac{\partial\rho}{\partial y'}+\rho\left(\frac{\partial V_x}{\partial x'}+\frac{\partial V_y}{\partial y'}\right)=0,$$
$$\frac{\partial V_x}{\partial t}+V_x\frac{\partial V_x}{\partial x'}+V_y\frac{\partial V_x}{\partial y'}=-\frac{1}{\rho}\frac{\partial p}{\partial x'},$$
$$\frac{\partial V_y}{\partial t}+V_x\frac{\partial V_y}{\partial x'}+V_y\frac{\partial V_y}{\partial y'}=-\frac{1}{\rho}\frac{\partial p}{\partial y'}. \tag{1}$$

Flow is assumed adiabatic $p/p_0=(\rho/\rho_0)^k$.

In case of steady-state flight conditions at a constant altitude h above the surface the system of equations could be regarded in the moving co-ordinate system $x=x'+Vt$, $y=y'$ (V is the parallel to surface flight velocity), where it takes the stationary form.

We assume disturbances being small and attack angle (α) being small as well, thus neglecting the second order of magnitude terms in linearization of system (1), which yields

$$\frac{1}{a^2}\frac{\partial p}{\partial t}+\rho_0\left(\frac{\partial V_x}{\partial x'}+\frac{\partial V_y}{\partial y'}\right)=0,\quad p=p_0+a^2(\rho-\rho_0),$$
$$a^2=\left.\frac{dp}{d\rho}\right|_{\rho=\rho_0}\quad \frac{\partial V_x}{\partial t}=-\frac{1}{\rho_0}\frac{\partial p}{\partial x'},\quad \frac{\partial V_y}{\partial t}=-\frac{1}{\rho_0}\frac{\partial p}{\partial y'}. \tag{2}$$

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