Earth – Mars Similarity Criteria for Martian Vehicles

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DOI: 10.13111/2066-8201.2010.2.3.9

Abstract: *In order to select the most efficient kind of a martian exploring vehicle, the similarity criteria are deduced from the equilibrium movement in the terrestrial and martian conditions. Different invariants have been obtained for the existing (entry capsules, parachutes and rovers) and potential martian exploring vehicles (lighter-than-air vehicle, airplane, helicopter and Mars Jumper). These similarity criteria, as non dimensional numbers, allow to quickly compare if such a kind of vehicles can operate in the martian environment, the movement performances, the necessary geometrical dimensions and the power consumption. Following this way of study it was concluded what vehicle is most suitable for the near soil Mars exploration. "Mars Rover" has less power consumption on Mars, but due to the rugged terrain the performances are weak. A vacuumed rigid airship is possible to fly with high performances and endurance on Mars, versus the impossibility of such a machine on the Earth. Due to very low density and the low Reynolds numbers in the Mars atmosphere, the power consumption for the martian airplane or helicopter, is substantial higher. The most efficient vehicle for the Mars exploration it seems to be a machine using the in-situ non-chemical propellants: the 95% CO2 atmosphere and the weak solar radiation. A small compressor, electrically driven by photovoltaics, compresses the gas in a storage tank, in time. If the gas is expanded through a nozzle, sufficient lift and control forces are obtained for a VTOL flight of kilometers over the martian soil, in comparison with tens of meters of the actual Mars rovers.*

Key Words: similarity criteria, Mars rovers, helicopter or Mars Jumper type

1. INTRODUCTION

The concept of "the in-situ non-chemical propellant production on the martian surface" has been introduced in 1993 when different types of exploring machines using the martian disposable energy (the weak solar radiation and the rarefied atmosphere) have been proposed. Martian missions with autonomous robots of rovers, airship, airplane, helicopter or Mars Jumper type, propelled by the solar energy have been analyzed [1]...[8]. The solar energy is converted in electricity by the photovoltaic cells and is used in real time or, in order to obtain more power, is stocked.

Table 1. Characteristics of the martian atmosphere

Nr.	Normalized parameter	Symbol	Value	Nr.	Normalized parameter	Symbol	Value
1	day duration	*sol*	1.	9	specific heats ratio	$\bar{\kappa}$	0.92028
2	gravity acceleration	$\bar{g}$	0.3953	10	sound speed	$\bar{a}$	0.665
3	pressure	$\bar{p}$	0.007	11	Mach number	$\overline{M}$	1.523

4	density	$\bar{\rho}$	0.0146	12	dynamic viscosity	$\bar{\mu}$	0.72124
5	temperature	$\bar{T}$	0.868	13	kinematic viscosity	$\bar{\nu}$	49.1
6	solar constant	$\bar{k}_S$	0.4316	14	Reynolds number	$\overline{Re}$	0.0204
7	gas constant (state equation of gases)	$\bar{R}_g$	0.658	15	laminar skin friction coefficient	$\bar{C}_{fl}$	7.0
8	molecular mass	$\bar{M}_m$	1.5605	16	turbulent skin friction coefficient	$\bar{C}_{ft}$	2.18

Martian atmosphere composition: 95% CO_2, 2.7% N_2, 1.6 %Ar. The exponential decrement of the martian atmosphere ($\rho = \rho_0 e^{-k_z z}$); $k_z = 0.000227756$/m.

An important part of the total mission cost is represented by the numerous tests, performed in special terrestrial installations simulating the martian conditions. It is more convenient to test a martian vehicle in the earthly surroundings and from the obtained results, based to the similarity criteria, to obtain the performances in the real martian atmosphere, than to build sophisticated devices simulating the martian gravity, soil, temperature, solar radiation, pressure, density. In the Table 1 are the some characteristics of the martian environment, normalized to the terrestrial values.

2. EARTH-MARS SIMILARITY CRITERIA FOR AN AEROSHELL AT THE ENTRY IN THE ATMOSPHERE (AEROBRAKE) AND FOR THE SOFT LANDING BY PARACHUTES

In general, a Mars-Earth similarity criterion is the ratio between the martian and the terrestrial values of the same parameter of the flow. During the entry in atmosphere the thermal transfer is crucial for the mission success. At high hypersonic Mach numbers the similarity criteria for a detached normal shock wave in front of a blunt body type entry capsule are given by the relations of Table 2, subscripts “1”, ”2” denoting the values in front and behind the shock wave, “E”- Earth conditions. In the same manner, similarity criteria were deduced for the Prandtl-Meyer expansion, for the oblique shock waves and for the isentropic flow [12]. The above Mars-Earth similarity criteria show that the thermal and mechanical stresses during the entry in the Mars atmosphere are higher (not in the absolute values) than in terrestrial atmosphere.

The viscous flow around an entry capsule of STARDUST type was numerically simulated by solving the Navier-Stokes equations, and various temperature, pressure and density maps are plotted in [1].

The equation of movement describing the deceleration of an entry capsule with parachute in martian and terrestrial atmosphere was solved for the following input data [9] and the results are given in Table 2.

- reference surface of the capsule/parachute=2sq.m/400 sq.m
- weight on the Earth = 100.0 kg
- mean drag aerodynamic coefficient capsule/parachute=0.5/1.25
- initial vertical velocity/ initial ceiling=2500m/s//100km
- the altitude of parachute deployment = 5 km

Table 2 Mars-Earth similarity criteria for normal shock wave in hypersonic flow

pressure	density	temperature
$\frac{\overline{p}_2}{\overline{p}_1} \cong \frac{\overline{\kappa}(\kappa_E+1)\overline{M}^2}{\overline{\kappa}\kappa_E+1} =$ 2.34	$\frac{\overline{\rho}_2}{\overline{\rho}_1} \cong \frac{(\overline{\kappa}\kappa_E+1)(\kappa_E-1)}{(\overline{\kappa}\kappa_E-1)(\kappa_E+1)} =$ 1.322	$\frac{\overline{T}_2}{\overline{T}_1} = \overline{\kappa}\overline{M}^2 \frac{(\kappa_E+1)^2(\overline{\kappa}\kappa_E-1)}{\overline{\kappa}\kappa_E+1)^2(\kappa_E-1)} =$ 1.693

Table 3. The soft landing by parachutes

	Touchdown velocity (m/s)	Time to touchdown (seconds)
Mars	9.23	415.0
Earth	1.77	2690.0

Despite the low value of the gravitational acceleration, due to the low density of the martian atmosphere, retro-rockets or airbags are necessary to ensure the soft landing on the Mars surface.

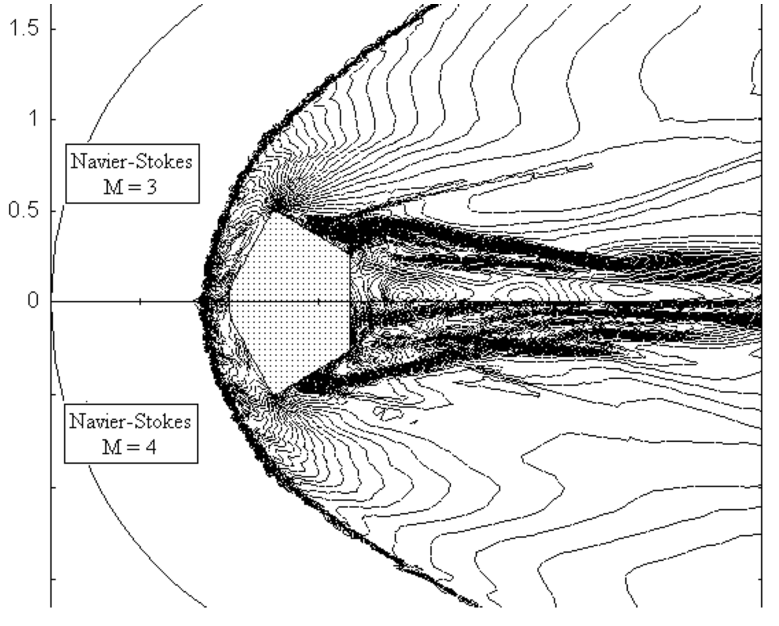

Fig.1. The isothermal lines around an entry body in the terrestrial atmosphere [12]

3. EARTH-MARS SIMILARITY CRITERI FOR A VEHICLE OF “MARS ROVER” TYPE

There are numerous and different projects for Mars exploration, but the successes have been obtained by the satellites, fixed stations (Mariner, Viking) and rovers. The displacement performances of a martian rover are limited by the severe climate conditions and by the rugged soil.

The rolling friction force (Fig.2) is:

$$F_f = \frac{f}{r} F_n = \frac{f}{r} G = \frac{f}{r} mg \tag{1}$$

F_f - friction force, F_n - normal force, G - weight, m – mass

$$\frac{f}{r} = \mu_r \quad \text{- rolling friction coefficient} \tag{2}$$

The similarity criterion for the horizontal traction:

$$\overline{F}_f = \frac{F_{fMars}}{F_{fEarth}} = \overline{g} = 0.39535 \tag{3}$$

The second Newton law for the horizontal displacement:

$$F = m\ddot{x} + \mu_r mg \tag{4}$$

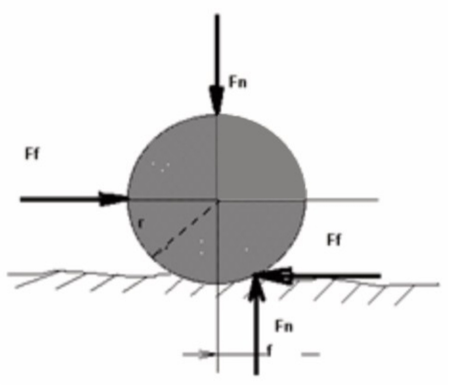

Fig. 2. Rolling friction

$$F = \frac{M}{r} \tag{5}$$

M –moment of friction, r – wheel radius

$$F = \frac{N}{\omega r} \tag{6}$$

N – actual power, ω - angular velocity

$$\dot{x} = \omega r \quad \text{- tangential velocity} \tag{7}$$

The movement equation:

$$N = m\dot{x}\ddot{x} + \mu_r mg\dot{x} \tag{8}$$

This equation is integrated for different types of energy supplying (Table4)

Table 4. The movement of martian rover

Nr.	Type of supplying	Similarity criteria			
		Velocity $\overline{\dot{x}}$	Distance $\overline{x}$	Power $\overline{N}$	Time of supplying $\overline{\tau}$
1	Rover with piston combustion engine (hydrazine)	$\overline{\dot{x}} = \frac{1}{\overline{g}^2}$ =6.397	$\overline{x} = \frac{1}{\overline{g}^2}$ =6.397		

2	Rover with piston engine (cold compressed gas)	$\bar{\dot{x}} = \dfrac{1}{\bar{g}^2}$ =6.397	$\bar{x} = \dfrac{1}{\bar{g}^2}$ =6.397		$\bar{\tau} = \dfrac{\bar{L}}{\bar{k}_S}$ =21.07
3	Rover with electro-motor supplied by photovoltaics (in real time)	$\bar{\dot{x}} = \dfrac{\bar{k}_S}{\bar{g}}$ =1.091	$\bar{x} = \dfrac{\bar{k}_S}{\bar{g}}$ =1.091	$\bar{N} = \bar{k}_S$ =0.4316	$\bar{\tau} = 0$
4	Rover with electro-motor supplied by battery	$\bar{\dot{x}} = \dfrac{1}{\bar{g}}$ =2.529	$\bar{x} = \dfrac{1}{\bar{g}}$ =2.529		$\bar{\tau} = \dfrac{1}{\bar{k}_S}$ =2.317

The deduced similarity criteria for different wheeled vehicles demonstrate higher movement performances on the Mars soil versus the Earth, even for a rover supplied in real time by photovoltaics, due to the low gravity. It remains the disadvantages of the rugged terrain.

4. EARTH-MARS SIMILARITY CRITERIA FOR A LIGHTER-THAN-AIR VEHICLE (BALLOON AND RIGID AIRSHIP)

For an inflated balloon, the Earth-Mars similarity criterion for the lifting force $\bar{P}$ is deduced writing the Archimedes principle for Mars atmosphere and for the terrestrial conditions [8]:

$$\bar{P} = \frac{\bar{p}\bar{g}}{\bar{R}\bar{T}} \frac{1 - \bar{R}\delta(1 + \lambda\bar{p})}{1 - \delta(1 + \lambda)} \tag{9}$$

$\delta = \dfrac{R_{aE}}{R_{gE}}$ the ratio of the gas constant of terrestrial atmosphere (aE) and balloon gas (gE) (10)

$\lambda = \dfrac{\Delta p_E}{p_{aE}}$ the balloon filling ratio, $\Delta p_E = p_{gE} - p_{aE}$ (11)

Using the values of Table 1, for a balloon with Helium or Hydrogen, the maximum lifting force ratio is about 0.005 for the same volume. For the same weight, in the martian atmosphere a balloon having a volume of 200 times greater than on the Earth is necessary.

An ideal lighter-than-air vehicle is a rigid vacuumed shell. This not so new idea was proposed by Francesco de Lana in 1670 [11]. He imagined four vacuumed copper spheres producing the Archimedes lifting force. Because the terrestrial pressure is 10 000 kg/sq.m such a vehicle cannot be build on Earth. It can be proposed an airship with folded rigid structure sent empty on the martian surface and after the inflating with the martian gas, the rigid structure being locked, ensuring the shape and volume. A small vacuum pump exhausts the gas and the lifting Achimedes force is produced. Such type of flying vehicle is realistic and is able to fly in the martian atmosphere because the maximum difference pressure is 70 kg/sq.m. It. can be designed an inner rigid structure resisting to the compression stresses generated by this moderate pressure difference.

The lifting force similarity criterion for a martian vacuumed airship is:

$$\overline{P} = \frac{\overline{pg}}{\overline{R}\overline{T}}\frac{1-\varepsilon_M}{\varepsilon_M} \tag{12}$$

$$\varepsilon = \frac{p_{inner}}{p_{ext}} < 1 \text{ the vacuum degree} \tag{13}$$

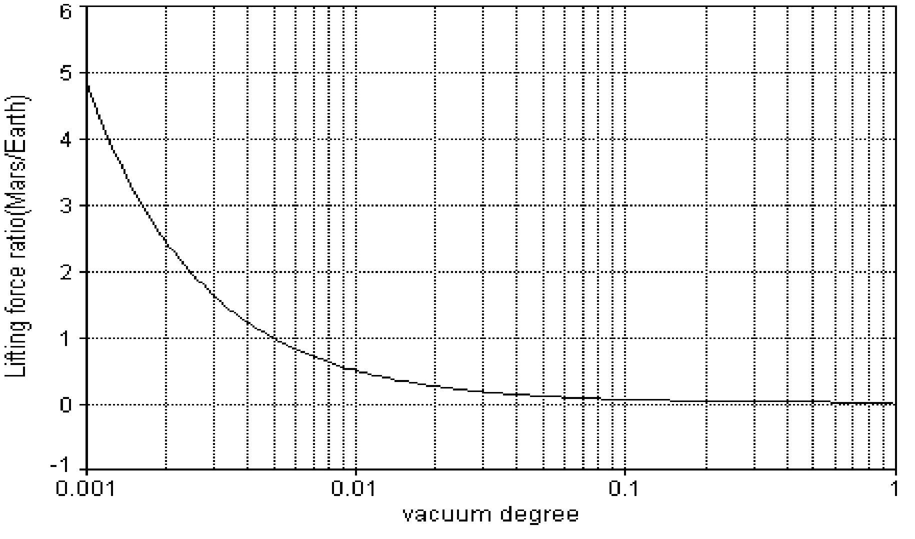

Fig. 4. The lifting force similarity criterion for a rigid vacuumed balloon

A vacuumed rigid balloon with at 0.005 degree of vacuum has the same lifting force with the hypothetical terrestrial lighther-than-air vehicle.

If the external surface of this rigid airship is covered by the photovoltaics, the collected electricity can supply an electro-motor rotating a propeller. The criterion for the velocity $\overline{V}$ of a rigid airship propelled by the solar energy is [12]:

$$\overline{V} = \left(\frac{\overline{k}_S}{\overline{\rho}\,\overline{C}_D^2}\right)^{\frac{1}{3}} = 0.874 \text{ for the laminar and } 1.902 \text{ for turbulent friction} \tag{14}$$

The criteria demonstrate that the actual philosophy of the terrestrial inflated balloons practically is not efficient for Mars, but an impossible vacuumed earthly balloon can be built to fly on Mars.

5. EARTH- MARS SIMILARITY CRITERIA FOR AN AIRPLANE

The idea of using wings to fly in the rarefied atmosphere of Mars was formulated by Wernher von Braun around 1940. Later, after the Mariner and Viking missions, when more accurate data about the martian environment were available, detailed calculations were made concerning an unmanned airplane.

The relations for lifting force (P), aerodynamic drag (R) and power (N) of an airplane, are written both for martian and Earth conditions, their ratios giving the similarity criteria.

$$\overline{P} = \overline{\rho}\overline{V}^2\overline{C}_L = \overline{g} \tag{15}$$

$$\overline{R} = \overline{\rho}\overline{V}^2\overline{C}_D \tag{16}$$

$$\overline{N} = \overline{\rho}\overline{V}^3\overline{C}_D \tag{17}$$

The value of ratios of the aerodynamic coefficients $\overline{C}_{L,}\overline{C}_D$ are obtained from the relations describing the influence of the Reynolds number on drag and lift (10).

Assuming that at low incidences the lift not depends by the Reynolds number ($\overline{C}_L \cong 1$)

$$\overline{C}_D = 1 + \frac{1.324}{C_{DE}}\left[\frac{1}{\sqrt{\mathrm{Re}_M}} - \frac{1}{\sqrt{\mathrm{Re}_E}}\right] \tag{18}$$

for laminar regime, and

$$\overline{C}_D = 1 + \frac{0.074}{C_{DE}}\left[\frac{1}{\mathrm{Re}_M^{0.2}} - \frac{1}{\mathrm{Re}_E^{0.2}}\right] \tag{19}$$

for turbulent (Re>500 000).

The values show a high power consumption for the flying in the martian atmosphere. *An airplane propelled by photovoltaics in real time, having the same dimensions and weight with a terrestrial one, cannot fly on Mars.* If the weight is similar, it must have a surface for the collection of the solar energy of 7.54 greater than an earthly solar airplane.

In [2],[4],[10] are described the results of a multi-objective, multi-parametric and multi-criterial aerodynamic optimization of an unmanned airplane configuration with solar propulsion in the martian atmosphere, the solar cells being mounted on the upper side of the airplane.

The configuration was defined by seven geometrical parameters (wing span, wing sweep angle, setting angles, etc.), these parameters playing the role of the independent variables in the optimization procedure. The scale factor was chosen to be the objective function in order to obtain the minimum geometrical dimensions, weights and power consumption for a given payload. In the Table 6 are illustrated the initial and final, optimized values of a configuration having the general view of Fig.5, designed to fly at 300 m in the martian atmosphere with 5 daN payload.

Table 5 Similarity criteria for different types of propulsion of an aircraft designed to fly on Mars

Nr.	Type of propulsion	Similarity criteria		
		Power $\overline{N}$	Surface of solar cells $\overline{S}_C$	Filling/releasing time ratio $\overline{\tau}_f / \overline{\tau}_r$
1	Propeller driven by combustion engine with hydrazine	$\overline{N} = \overline{C}_D\overline{g}\sqrt{\frac{\overline{g}}{\overline{\rho}}}$ =14.35 (laminar) = 4.47 (turbulent)	1	

2	Propeller driven by electro-motor supplied in real time by photovoltaics	1	$\bar{S}_c = \frac{\bar{g}}{\bar{C}_L}\left(\frac{\bar{C}_D}{\bar{\eta}_e k_S \sqrt{\bar{\rho}}}\right)^{\frac{2}{3}}$ = 7.54	
3	Propeller driven by electro-motor supplied by photovoltaics (compressed gas)	1	1	$\frac{\bar{\tau}_f}{\bar{\tau}_r} = \bar{\tau}_{f/r} = \frac{\bar{g}^{\frac{3}{2}}\bar{C}_D}{\bar{\rho}^{\frac{1}{2}}\bar{C}_L \eta_{cmp}\bar{\eta}_t\bar{\eta}_e k_S}$ =33.5

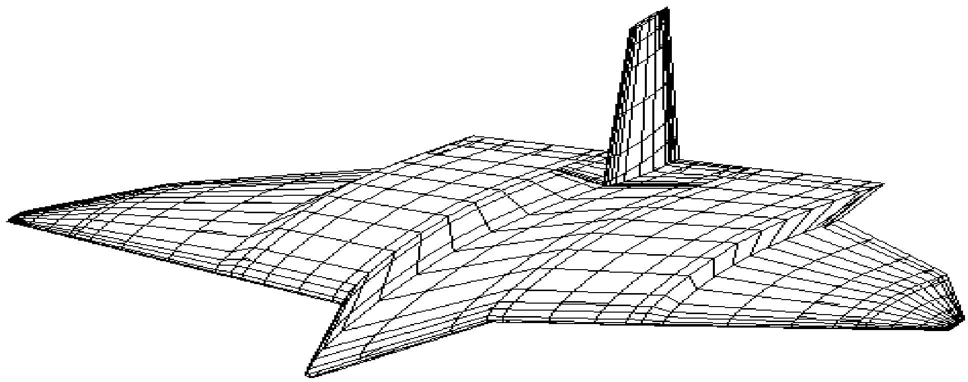

Fig. 5. General view of the optimized solar airplane

Table 6. Optimized solar Mars airplane

	Initial	Final (optimized)
Fuselage length (m)	6.155	4.683
Gross weight (daN)	58.57	34.53
Power (kW)	1.608	0.812
Speed (m/s)	63.35	58.21
CD/CL	0.10852	0.10113
Surface (sq.m)	27.44	13.71

The severe martian conditions (low atmosphere density and solar radiation) are responsible for the weak fight performances of a solar airplane. Even an optimized configuration requires a surface of 13.71 sq.m in order to fly 5 daN of payload.

6. EARTH-MARS SIMILARITY CRITERIA FOR A ROTORCRAFT VEHICLE (HELICOPTER)

A flying machine having vertical take-off/landing capabilities is interesting for Mars exploration in the conditions of the rugged terrain. In [3], [5] the advantages and disadvantages of using a helicopter for the Mars surface exploration were analyzed, for different types of power production: combustion engine with hydrazine, electro-motor supplied by photovoltaics in real time and electro-pneumatic system for energy stocking (Fig. 6). It was studied only the configuration with two co-axial rotors.

The power production system sketched in Fig. 6 is similar to that used for a martian airplane. The results are synthesized in Table 7. The electricity collected from the upper rotor by photovoltaics supplies the d.c. electro-motor driving a gas axial compressor and a piston compressor. The energy stocked in the pressure tank produces more power when the gas is expanded through the axial compressor, working now as a turbine. The turbine rotates the axial rotor of the helicopter through a reduction gear. The produced power is proportional with the filling/discharging time ratio of the pressure tank.

The similarity criterion for rotor polar (drag/thrust= $\frac{C_D}{C_T}$) depends by the Reynolds number ($\overline{C}_f$)

$$\overline{C}_D = \overline{C}_f - b\frac{C_{TE}^{\frac{3}{2}}}{C_{DE}}(\overline{C}_f - 1) \tag{20}$$

The similarity criteria show that in all cases of power production the rotor diameter for a martian helicopter has about double value versus one terrestrial, for the same payload.

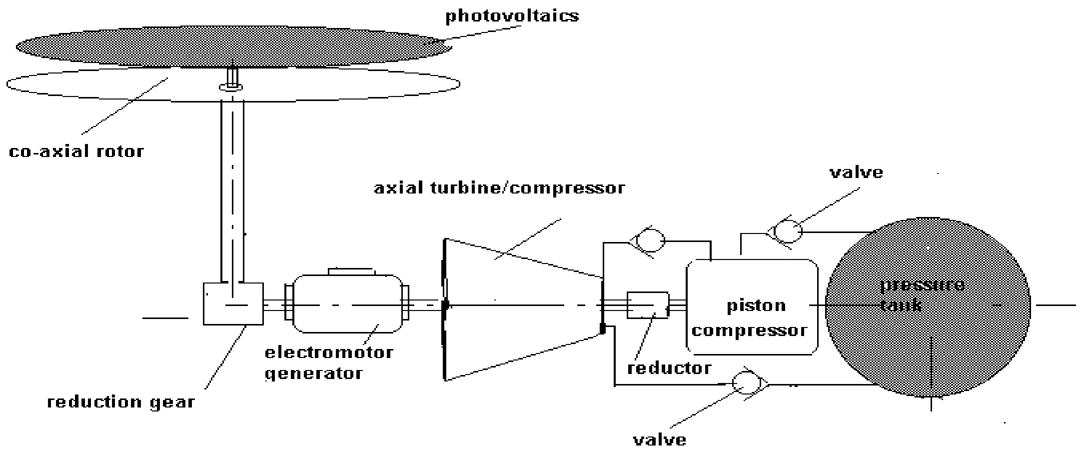

Fig. 6. The electro-pneumatic power production system

Table 7 Martian helicopter

Type of power production	Similarity criteria		
	Power (hovering flight)	Rotor diameter	Descending speed in auto-rotation
Piston thermal engine (hydrazine)	$\overline{N} = \sqrt{\frac{\overline{g}^3}{\overline{\rho}}}$ =2.05	$\overline{d} = \sqrt{\frac{\overline{g}^3}{\overline{\rho}}}$ =2.05	$\overline{V}_d = \sqrt{\frac{\overline{g}}{\overline{\rho}}}$ =4.1
Electro-motor supplied by photovoltaics in real time	$\overline{N} = \frac{\overline{g}}{\overline{k}_S}\sqrt{\frac{\overline{g}}{\overline{\rho}}}$ =4.75	$\overline{d} = \frac{\sqrt{\overline{g}}}{\overline{k}_S^{\frac{1}{3}}\overline{\rho}^{\frac{1}{6}}}$ =1.70	$\overline{V}_d = \sqrt{\frac{\overline{g}}{\overline{\rho}}}$ =4.1
Electro-motor with stocking energy system	$\overline{N} = \overline{k}_S$ =0.4316	$\overline{d} = \frac{1}{\overline{k}_S}$ =2.317	$\overline{V}_d = \sqrt{\frac{\overline{g}}{\overline{\rho}}}$ =4.1

7. EARTH-MARS SIMILARITY CRITERIA FOR A VEHICLE PROPELLED BY COLD JETS (MARS JUMPER)

The similarity criteria for flying vehicles for Mars exploration demonstrate high power consumption and large geometrical dimensions required. Taking into account the Mars environment particularities an ideal, vehicle must responds to the next requirements:

- to have small dimensions
- to use the in-situ disposable energy
- to fly over the natural obstacles
- to have take-of/landing vertical capabilities
- to have re-charging capabilities
- to have long time of exploitation

Such a type of vehicle was proposed in [6], [7], [8] and it was named “Mars Jumper“ or “Mars Hooper”. The working principle is based on the transformation of the non-chemical energy in mechanical or electrical energy.

The low density of energy existing on Mars surface (low atmosphere density and poor solar radiation) is stocked in time and transformation in shorter time producing the necessary power for displacements or for the supplying of the scientific devices. The block scheme is similar to the power production system for martian helicopters, described above (Fig.6). In the present case the pressure tank is discharged through vertical and horizontal nozzles, producing the lifting , propulsion and command forces for a controlled jump over the martian terrain. In [6],[7],[8] the equation of movement and the flow through the nozzles were simultaneously solved in time. A Mars Jumper having the compressed gas/total weight ratio=0.2332 can perform a controlled jump of 4.5 km at 450 m altitude and with a safe vertical landing on the martian soil, after 8 hours of pressure tank charging. The duration of flight is 48 seconds. The Earth-Mars similarity criteria for a Mars Jumper vehicle are given in Table 8.

Table 8. Mars Jumper

Criterion	Value
Time of pressure tank filling	$\tau_f = 3.19$
Time of pressure tank discharging	$\tau_d = 3.81$
Maximum distance	$\bar{x}_{\max} = 2.294$
Time of flight	$\bar{\tau} = 2.294$
Thrust of nozzle	$T\bar{r} = 1.309$
Work of compression	$\bar{L} = 1.378$

For the same payload the geometrical dimensions of Mars Jumper are substantial lower versus the martian plane or helicopter.

8. CONCLUSIONS

The deduced similarity criteria allow to compare the performances of the same type of martian exploring vehicle or to compare the efficiency of different kind of vehicles.

It was demonstrated that the vehicles based on the aerodynamic forces (airplane or helicopter) have low performances in martian atmosphere and large geometrical dimensions.

An impossible terrestrial vehicle (rigid vacuumed airship) can be built to fly in the martian environment.

It seems that a Mars Jumper type vehicle is feasible to be built and to perform martian explorations for long duration.

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