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Performing a Flight in the Jovian Stratosphere – Engine Concept

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Abstract The most effective method for a detailed observation of the Solar System planets is the use of vehicles that can perform flights in their atmospheres with the most promising of them being flyers (aircrafts for other planets atmospheres). Their advantage is the ability to collect information from a large areas and the option to select the direction and altitude of the flight. Among all the planets of the Solar System and their satellites Jupiter is the most promising option for conducting a flight since it has the most suitable atmospheric conditions for this, and just as importantly, there is enough data for designing a flyer. The aim of this article is to solve one of the first and most important problems, which naturally arise when we want to perform a flight in the atmospheres of planets in the Solar System, that is the choice of the propulsion type and the calculations of some main physical characteristics of the engine and the possible flight altitudes in the Jovian stratosphere for a two types of flyers with masses 1 and 2 tons.

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1 Introduction

From the beginning of the space era, over thirty probes have been sent into the atmosphere or landed on the surface of the other planets in the Solar system. However, most of them had no capability to fly. The only vehicles that successfully reached and conducted a flight in the atmosphere of a planet other than the Earth were Vega-1 and Vega-2 balloons in 1985 on Venus. They have flown over twenty thousand kilometers into it atmosphere and collected valuable scientific information [1,2]. Some future missions are in development phase right now, but none of them are considering the usage of flyer that uses classical airplane principals to perform a long atmospheric flight in planets other than Earth . Our aim is to discuss the possibilities and the principals that will allow us to perform a flight of that type using flying vehicles on Jupiter as a beginning.

The first problem to begin with is an engine that can give enough thrust to the flyer and to be simple enough – to have as few as possible moving parts, because every moving part is increasing the possibility of failure. The usage of electric engines with solar panels is not meaningful because in Jovian atmosphere we can gather only 6% of the solar energy that we can gather on Earth – no practical amount of thrust will be produced. This means that the flyer will not be able to resist the strong winds in the Jupiters atmosphere. Because of the presence of H_2 and even some NH_3 in the Jupiters stratosphere and troposphere the usage of internal combustion engine or a jet engine with combustor is possible if there is an oxidizing agent on board. They will provide enough thrust, but the time of flight will be limited up to several tens of hours because of the limitation in the oxidant mass that the flyer can carry. The usage of these engines will be unreasonable taking into account how expensive it is to deliver every kilogram in Jupiter atmosphere.

A reasonable option is the usage of Nuclear-Powered Ramjet Engine (NPRE). It can give enough thrust, the nuclear fuel mass is relatively small and it is simple – there are almost no moving parts. The aim of this article is to reveal the possibility and to calculate in first-order approximation the main characteristics of an engine of that kind that can fly in the Jovian atmosphere.

Such an engine has been tested on Earth and has shown great results within the US Military Project Pluto. In the tests, the engine thrust reached 156,000 N. The project envisaged the creation of a nuclear-powered supersonic rocket – SLAM (Supersonic Low Altitude Missile), which is capable of performing flights for a long time on complex trajectories. The project was closed in 1964 because the intercontinental ballistic missiles were preferred. However, for the time being, such an approach remains the most realistic to perform a flight in the atmospheres of Solar system planets.

Research on the topic was conducted by Miller K.L. et.al. 1995 [3]. They suggest that a flight could be performed with a 3-tonne flyer at a subsonic speed. The proposed flyer will use an engine that has a turbo compressor to compress the atmospheric gases, nuclear heat chamber and turbine – a classic turbo-jet engine only with a nuclear heat chamber instead of a combustion chamber. Considering the Jupiter's sound speed on that altitudes to achieve enough compression – the compressor will need very high speed of rotation and will, therefore, be subjected to enormous loads from centrifugal forces. This poses a greater risk of broken blades. Furthermore, in order to achieve sufficient compression of the gases, the compressor will have to be composed of several stages – more than similar engines on Earth have. This results in a significant increase in mass, production complexity and the risk of damage to the engine. Such a flyer still has chances to perform the flight, but because of the large number of moving parts in the engine, the risk of failure is significant. Considering how expensive such a mission would be, the risk of failure should be minimized as much as possible. This forces us to look for a minimal risk approach to the designed flyer. That is precisely why we think that the use of subsonic jet engines is undesirable compared to the ramjet engines.

The most in-depth research on the topic is made by Maise et.al. [4]. In their research, a principal design of such an engine was reviewed, which is an atmospheric variation of MITEE nuclear rocket engine [5]. Some main physical and geometric parameters of the engine are given, but no CFD simulations or tests in wind tunnel of their design have been carried out to confirm their conclusions.

For those reasons we aim to conduct a more in-depth analysis of the operation of such an engine. The atmosphere of Jupiter is chosen for the research, for which there is a significant amount of data, especially from the Galileo probe. This data is taken as a basis for the calculations [6].In addition, the planet is closer to the Earth than the other gas giants and has a large number of atmospheric features that are interesting for exploration. The methodology for calculation of the engine parameters is taken from the textbook of Bondaryuk and Il'yashenko, 1958 [7].

2 The Enviroment

The atmosphere of Jupiter is gigantic. For conducting a flight, it is best to consider only the lower part of the stratosphere and the upper part of the troposphere. The Jupiter Sea Level (JSL) is defined as the level where the pressure is equal to 1 Bar. At that level the surface gravity is $g_{Jup} = 2.528\, g_{Earth} = 24.79$ m/s^2. For an upper limit of the calculations we have chosen the altitude of 90 km above the JSL, because the density on that level $\rho_{90km} = 0.0018$ kg/m^3 is approximately the same as the density of the air on Earth 50 km above the sea level. For the lower limit the altitude is chosen to be 23.5 km, because we have full data from Galileo probe above this level. For lower attitudes there is no data for the heat capacity ratio, the gas constant and the local speed of sound, although they do not change significantly and the values can be approximated.

The composition of the gas at these altitudes is approximately 86.1 % H and 13.6% He. The remaining gases and the change in the H/He ratio are an insignificantly small fraction and their presence is taken into account in the heat capacity ratio, the gas constant and the speed of sound data from the Galileo probe.

The haze layer starts at around 50 km above JSL and starts to convert to ammonia cloud layer at around 30 km that contains ammonia ice particles. The bottom end of the ammonia clouds is at around 0 km. The flight must be conducted mostly on levels above the cloud layers, because of the opportunity to observe visually the surrounding area without being blinded by the clouds.

3 The Calculation approach

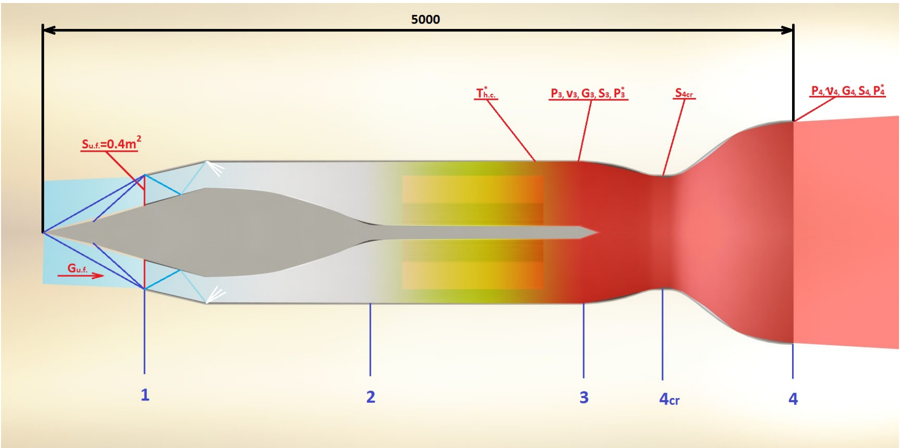

Fig. 1 Engine schematics and sections: 1 Inlet entrance, 2 Diffuser, 3 Heat chamber exit, 4cr Critical nozzle section, 4 Nozzle outlet. The notation for the relevant physical parameters for each section is also given.

The formula for the thrust of the NPRE can be defined from the main formula of the effective thrust and it is

$$R = G_4 v_4 - G_{u.f.} v_{u.f.} - (p_4 - p_{u.f.}) S_4 - X_\alpha \tag{1}$$

where $G_{u.f.}$, G_4 , $p_{u.f.}$, p_4, $v_{u.f.}$ and v_4 are atmospheric gas mass flow rate, pressure and velocity of the undisturbed flow and on the nozzle outlet section, R is the thrust produced by the engine and X_a is the additional resistance. In every case in which the oblique shock waves move away from the front edge additional resistance occurs, which is determined experimentally. The inlet can be designed in such a manner so that X_a is zero or negligible, i.e. oblique shock waves focus on the front edge of the diffuser.

If the nozzle is designed so that it can allow the outflow pressure p_4 to drop to $p_{u.f.}$ then

$$(p_4 - p_{u.f.})\, S_4 = 0. \tag{2}$$

For the NPRE $G_4 = G_{u.f.}$ because there is no additional fuel flow inside the contour, i.e. there is no combustor, only a heat chamber, the mass flow rate of the gas does not change inside the engine. As a result the thrust will be

$$R = G_{u.f.}(v_4 - v_{u.f.}). \tag{3}$$

The undisturbed flow speed is determined by the speed of the flyer in Mach (M), which can be chosen as a free parameter, and the sound speed of the environment (c), which we know from the Galileo probe. Then $v_{u.f.} = cM$. The mass flow rate of the gas is $G_{u.f} = S_1 \rho_{u.f.} v_{u.f.}$, where S_1 is the inlet surface which for the purpose of this article is chosen to be $S_1 = 0.4$ m^2, with the main motivation being engine compactness. The values of $\rho_{u.f.}$ are taken from the Galileo probe data. The speed of the outflow on the end of the nozzle is

$$v_4 = \sqrt{2\,\frac{\gamma}{\gamma - 1}\, R_{gas} T^*_{h.c.} \left[1 - \left(\frac{p_{u.f.}}{\sigma_n p^*_3}\right)^{\frac{\gamma-1}{\gamma}}\right]}, \tag{4}$$

where γ is the heat capacity ratio of the gas, R_{gas} is the specific gas constant for the fluid, $T^*_{h.c.}$ is the gas temperature, σ_n is a nozzle dependent coefficient and p^*_3 is the pressure of the stagnated flow after the heat chamber.

The heat capacity ratio γ will change with the temperature $T^*_{h.c.}$, but because the H_2 is the main component in the gas mixture it varies between $\gamma = 1.35 \div 1.45$ for temperatures $T^*_{h.c.} = 200 \div 1500$°K. Therefore, a reasonable choice would be to set $\gamma = 1.4$. The specific gas constant R_{gas} is taken directly from the Galileo's measurements for the different altitudes. $T^*_{h.c.}$ can be chosen as a free parameter and σ_n can be determined for a specific nozzle trough Computational Fluid Dynamics (CFD) simulations or by testing the nozzle in the same environment and in the same conditions, which requires the construction of specialized testing facilities. For the purpose of this article, in first approximation $\sigma_n = f\left(\frac{s_4}{s_3}\right) = \frac{p^*_4}{p^*_3} = 0.3$. The pressure of the stagnated flow p^*_3 can be calculated from the formula

$$p^*_3 = \sqrt{\frac{R_{gas}}{\gamma}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}}\,\frac{\beta\, G_{u.f.}\sqrt{T^*_{h.c.}}}{\sigma'_n\, S_{4cr}}. \tag{5}$$

Here $\sigma'_n = 0.7$ is chosen from statistical considerations (compared with engines that are used on Earth) and $S_{4cr} = 0.25$ is chosen from design considerations. Exact values of those coefficients is an issue for a future theoretical and experimental work.

After calculating the thrust, it is possible to calculate the lifting force under certain conditions. It is necessary to consider the flight as steady for different altitudes. In this case, the gravitational forces will be equal to the lifting forces and the drag will be equal to the thrust. Thus, we can relate them with the Lift-to-Drag ratio (L/D ratio) $k = \frac{L}{D}$. The L/D ratio can be calculated with the Küchemann's relationship

$$k_{max} = \left(\frac{L}{D}\right)_{max} = \frac{4(M+3)}{M}, \tag{6}$$

where M is the Mach number. For $M = 3$ it will be $k = 8$, but this relationship is approximately valid for air and is not necessarily true for other gases. There are no designed flyers that are tested in wind-tunnel and there are no CFD simulations that were performed (it is a matter of future work) to give an idea what L/D ratio can be reached. Based on data of the hypersonic aircrafts and rockets that flied in Earths atmosphere and the difference in the critical Reynolds numbers, we can assume that L/D ratio of $k = 5$ can be reached while designing the Jupiters flyer. For the case of steady flight the lifting force then can be calculated from the thrust

$$k = \frac{L}{D} = \frac{F_{gravity}}{P}. \tag{7}$$

From the relationship $F_{gravity} = kD = kP = 5P$ it is possible to calculate some main characteristics for a steady flight on different altitudes. If the lifting force is known, it is possible to make a conclusion for the mass of the flyer that can perform a steady flight at different altitudes. The results from the calculations are shown in the figures below for four different temperatures $T^*_{h.c.} = 1500°K; 1200°K; 900°K; 600°K$.

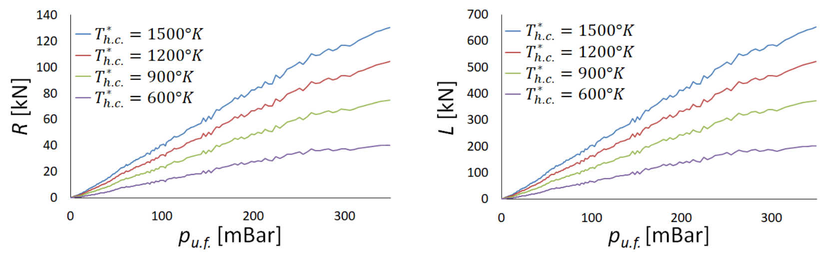

Fig. 2 Dependence of the thrust R produced by the engine and the lift force L from the atmospheric pressure $p_{u.f.}$ calculated for four different temperatures of the stagnated flow in the engine heat chamber.

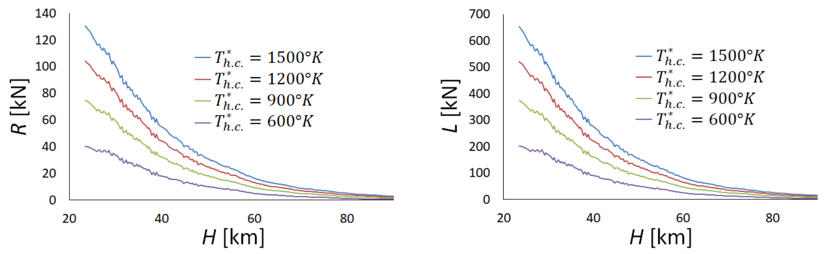

Fig. 3 Dependence of the thrust R produced by the engine and the lift force L at different altitudes H calculated for four different temperatures of the stagnated flow in the engine heat chamber.

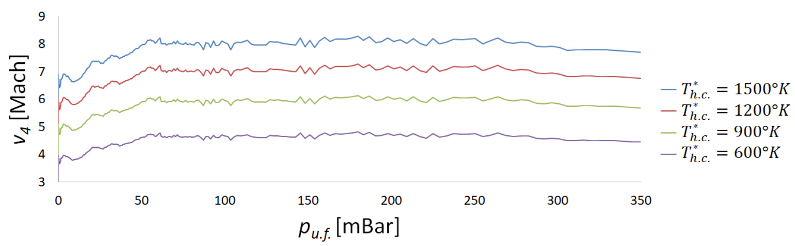

Fig. 4 Dependence of velocity of exhaust gases v_4 from the atmospheric pressure $p_{u.f.}$

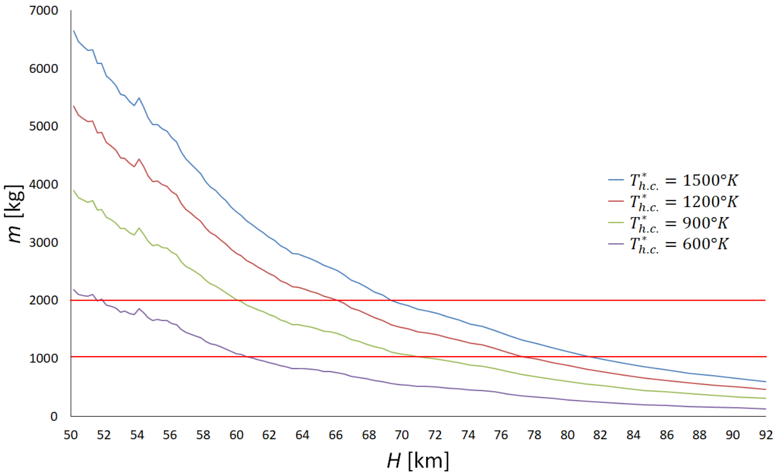

Fig. 5 Dependence of the mass of the flyer that can perform steady flight at alttitude H above JSL. The horizontal lines represent the masses of the two flyers - 1000 kg and 2000 kg.

As a result of the calculations of the thrust and the lift force at various temperatures inside the heating chamber, it is possible to conclude at what altitudes a steady flight of the flyer can be achieved (Figure 5 and Table 1). Two possible masses of the flyer are taken into account – 1000 kg and 2000 kg.

Table 1 Dependence of the altitude of steady flight H from the temperature of the heat chamber $T^*_{h.c.}$ for the two flyers.

$\mathbf{T^*_{h.c.}}$ [°K]	**Altitude of steady flight with flyer mass of 1000 kg, given in [km]**	**Altitude of steady flight with flyer mass of 2000 kg, given in [km]**
1500	81	69
1200	77	66
900	72	60
600	61	52

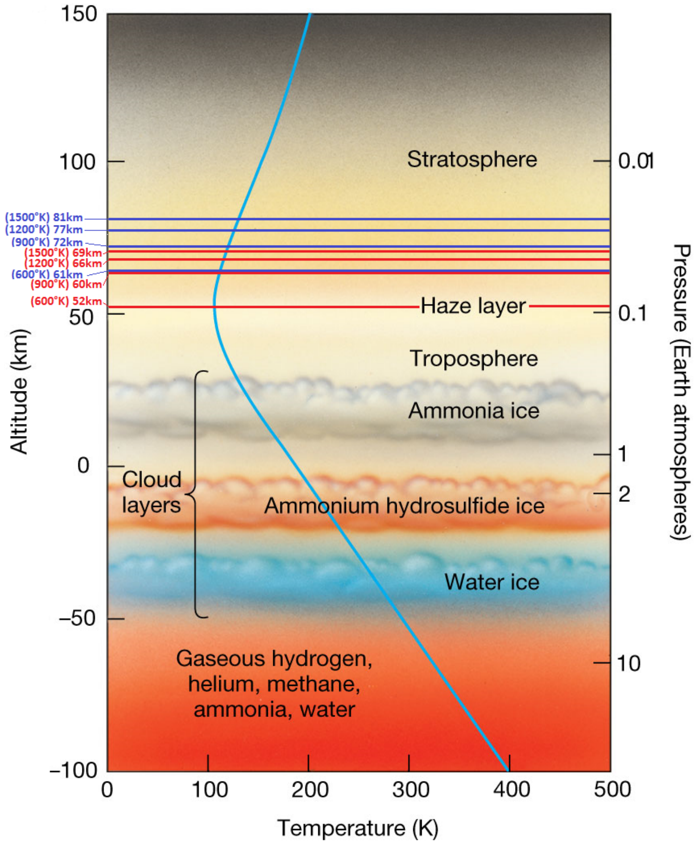

Fig. 6 Dependence of the altitude of steady flight from the temperature of the heat chamber $T^*_{h.c.}$ for the two flyers. The horizontal blue lines represent the 1000 kg flyer and the red ones the 2000 kg one. Source picture is taken from Pearson Education, Inc.

4 Conclusion

In the first-order approximation, it is apparent that the usage of NPRE that works with the gases from the Jovian atmosphere is possible. Such an engine can produce more than enough thrust for the future flyer. This is due to the physical characteristics of the gases. The lower layers of the Jupiter stratosphere are dense enough to allow its efficient operation. In addition, the gases from which the atmosphere is composed can be heated to sufficiently high temperatures, due to the high heat capacity of hydrogen and helium.

However, much work has to be done in the future. For more accurate calculation of the parameters of such an engine, a specific engine design must be chosen in which the full appearance of all engine components must be defined – the intake, the diffuser, the heating chamber, and the nozzle. For the different altitudes above JSL, the engine designs will be different and each of them will be a matter of further specific researches. CFD simulations have to be done for the second-order approximation to compare the results with the calculations. Testing of such an engine in wind tunnel in near to the real conditions will be the best approach, but this will be a very difficult task, considering the composition and temperature of the gases, the speed at which such an engine works and other factors.

Yet the benefits of creating engines that can give to flyers enough thrust to fly into the atmosphere of Solar System planets are significant. Apart from Jupiter, such devices can also perform flights in the atmospheres of other celestial bodies – Saturn, Uranus, Neptune, Venus and Titan. Apart from the purely scientific interest in the celestial bodies, there is also a very pragmatic interest – the resources. Considering the presence of large quantities of powerful energy resources, such as He-3 on some of these planets, such missions may prove to be beneficial.

Conflict of interest

The authors declare that they have no conflict of interest.

5 Acknowledgments

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6 Appendix

6.1 Some Abbreviations

JSL – Jupiter Sea Level = 0 km The level of pressure equal to 1 Bar

NPRE – Nuclear-Powered Ramjet Engine

Flyer – Flying vehicle similar to plane, but flying in the atmosphere of other celestial bodies

CFD - Computational fluid dynamics

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