Calculation of the optimal diameter of the air intake of the propulsion system for small spacecraft

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Abstract. The article presents the calculation of the optimal diameter of the mesh channel of the air intake of the propulsion system of a small spacecraft, which operates on outboard air. Graphs of the dependence of the efficiency of the air intake on its diameter, the dependence of the mass flow rate of particles on the diameter of the air intake are obtained. The analysis of the environmental friendliness of creating a propulsion system by the EIO method is carried out. The assessment of the harmfulness effect of the device on the environment during its operation was carried out.

1. Introduction
The propulsion system in the outboard air collects particles of the residual atmosphere and uses them as a working fluid for the electric rocket engine in order to compensate for the braking force acting on the spacecraft. The system theoretically allows the satellite to stay in orbit for an unlimited amount of time without a reserve of working fluid. Various types of engines can be used in the outboard air system, but in most of them there is a resource limitation associated with the erosion of individual structural elements. In this sense, electrodeless engines are more promising, since their elements are practically not subject to erosion.

A significant interest in the class of electrodeless engines is the engine based on the helicon discharge. Recent studies have shown that such engines can provide significant traction efficiency and high specific impulse due to the effective contribution of electrical power to the discharge and the high degree of ionization of the working fluid compared to other non-electric motors. Various new technical solutions have made it possible to increase its efficiency and compete in a number of tasks with classic
types of engines like Hall and ion. Currently, in accordance with the ideology of unlimited resource, the helicon engine is the most promising for use as part of an outboard air propulsion system.

2. Main part
The article contains calculations for a propulsion system capable of maintaining the orbit of a small spacecraft in a circular Earth orbit with an altitude of 200 km, with a period of active existence of at least 5 years. The main task of the apparatus is to conduct radar reconnaissance.

A typical outboard air installation consists of an air intake, a manifold, and an electric rocket motor. The collector is installed to thermalize the particles and reduce their return flow. The principle of its operation is shown in figure 1.

![Figure 1. The principle of operation of the collector.](image)

The principle shown in figure 1 is based on the fact that the velocity vector of the collected particles takes on a random direction when they first hit inside the collector. This makes it difficult for the particles to flow back through the inlet channel, as they often experience a large number of collisions with the channel walls before escaping back into the environment.

The operation of the entire propulsion system is determined by the air intake. Its important parameter is diameter. When choosing a diameter, there are two size restrictions. The minimum diameter of the air inlet is set by the mass air flow, at which a helicon discharge is capable of igniting at an acceptable level of input power. The maximum diameter is limited by the electrical power that is allocated for the needs of the electric rocket engine. The larger the diameter of the air intake, the greater the force of aerodynamic drag and, accordingly, the greater the required engine thrust and power consumption.

The calculation of the parameters of the air intake can be carried out by considering the balance of the flow rates of air entering and leaving the engine.

![Figure 2. Design scheme of the air intake.](image)
3. Assumptions
Four assumptions were accepted:

- Incident particles freely enter the air intake. So we can consider a problem in which a given flow rate \( m \) falls into the reservoir volume \( N \). This flow rate at a known flight altitude will depend only on the inlet diameter of the air intake.
- The flow of incident particles does not interact with the side walls of the initial tract.
- Reverse flow and flow of particles to the engine - thermalized.
- There are no collisions of particles with each other.

The reverse current from the air intake is represented by three components:

- Thermalized flow driven by pressure gradient
- Particles reflected from the walls of the air intake
- Particles that have changed their direction to the opposite as a result of collisions with other particles

It is obvious that the greater the degree of pressure increase in the air intake, the greater the contribution is made by the first and third components.

The return current from the air intake is determined by the pressure difference created in it. Also, in the calculations, we will neglect the effect of the incident flow of particles, which reduces the value of the reverse current.

In this case, we can use the usual equations of vacuum technology to estimate the flow.

Since the incident particles freely enter the air intake, we can consider the problem in which a given flow rate \( m \) falls into the collector volume \( N \). This flow rate at a known flight altitude will depend only on the inlet diameter of the air intake.

Two thermalized flows leave the system: the flow into the engine, which depends on the conductivity (diameter) of the hole \( d_0 \) and the pressure drop (compression ratio in the manifold); backflow to atmosphere. The air intake works the more efficiently, the lower the return conductivity of the inlet line, since it limits the amount of return flow.

4. Efficiency of the mesh air intake
The flow of incoming particles:

\[
m_{in} = \rho V \frac{\pi d^2}{4}
\]  

(1)

Pipe conductivity in molecular mode [1]:

\[
U_m = 38.1 \frac{d^3}{L} \sqrt{\frac{T}{M}}
\]  

(2)

The gas flow at a known pressure difference and line conductivity is determined:

\[
Q = (p_1 - p_2)U
\]  

(3)

Where \( p_1 \) - overboard pressure, \( p_2 \) - manifold pressure.

The mass flow rate is related to \( m \) is related to the gas flow \( Q \) as follows:

\[
Q = \frac{m \cdot R \cdot T}{M}
\]  

(4)

The efficiency of the mesh air intake is defined as the ratio of the number of particles entering it to the number of particles leaving the engine [2].

The efficiency of the air intake is reduced due to the sum of two streams leaving through the inlet section: reverse thermalized particle flow, and the flow of geometrically reflected particles.
The value of the first flow can be estimated by assuming the pressure in the manifold is known and calculating the conductivity of the line. In this case, we assume that the flow of incident particles does not affect the conductivity of the main line [3].

5. Hole conductivity in forward and reverse modes

Hole conductivity in molecular mode:

\[
U_{om} = 28.6d_0^2 \sqrt{\frac{T}{M}}
\]  

The leakage flux is defined as:

\[
Q = \frac{\dot{m} \cdot R \cdot T}{M}
\]  

Then the pressure difference is:

\[
(p_1 - p_2) = \frac{Q}{U}
\]  

Figure 3. Air intake mesh channel.

Consider the reverse conductivity of the mesh air intake. The number of cells inside the air intake can be obtained as:

\[
K = \pi \left( \frac{d}{a} \right)^2
\]  

We assume that the area of all cells, including those located along the radius, is equal to \( F = a^2 \) [4]. Then the reverse conductivity of the air intake:

\[
U_{kv} = 38.1K \frac{a^3}{L} \sqrt{\frac{T}{M}} = 30.0 \left( \frac{a \cdot d^2}{L} \right) \sqrt{\frac{T}{M}}
\]  

Pressure ratio:

\[
\frac{p_1}{p_2} = \frac{\dot{m} \cdot T \cdot R}{M(U_{kv} + U_{om})}
\]  

The ratio of reverse flow and flow to the engine is equal to the ratio of the corresponding conductivities [5, 6]. Then the efficiency of the air intake:

\[
\eta_c = \frac{U_{om}}{(U_{kv} + U_{om})} \frac{\dot{m}_{kv}}{\dot{m}_{om}} = \frac{\dot{m}_{kv}}{\dot{m}_{in}}
\]  

\[
\dot{m}_{kv} = \eta_c \cdot \dot{m}_{in}
\]
where $m_{in}$ - mass flow into the engine. Let's build a graph of the dependence of the mass flow rate into the engine on the diameter of the air intake.

**Figure 4.** Dependence of the mass flow rate on the diameter of the air intake.

**Figure 5.** Dependence of the efficiency of the air intake on its diameter.
6. Environmental assessment

Harmful emissions are substances that, upon contact with the human body, can cause diseases or deviations in the state of health, both immediately after exposure to the body, and in the long-term life of the present and subsequent generations.

During an experiment in a laboratory that simulates the operation of a real machine, the mid-range ultraviolet radiation generated by the propulsion-power plant passes through a quartz optical window without experiencing significant absorption. Ozone is being produced. The energy of ultraviolet radiation is small, and since for HF plasma the characteristic values of the volumetric concentration are $10^{17} - 10^{18}$ m$^{-3}$, it can be concluded that ozone will be generated in safe volumes that do not have a harmful effect on humans.

During the operation of the experimental setup, in particular, the rotary vane pump of the foreline stage of the pumping system, oil vapor is released. The manufacturer of the pump, under the conditions of ensuring the technical serviceability of the product, timely maintenance and the use of original oil, guarantees a practically "oil-free vacuum". However, oil can enter the laboratory through the pump exhaust. To eliminate possible air pollution in the room, a channel is connected to the pump exhaust to remove oil vapors into the open space. As an additional protection measure, it is recommended to install an air extraction unit in the room.

The analysis of the stand allows us to conclude that the test facility is environmentally friendly. However, do not forget that during the production of any, even environmentally friendly products, certain harm is caused to the environment. In 2019, the Russian Federation ratified the Paris Agreement, which stated that this harm can be measured by analyzing the amount of carbon dioxide CO$_{2e}$ emitted during the production of plant precursors.

The carbon footprint in this case is the aggregate of all greenhouse gas emissions produced directly and indirectly during the production of the studied installation. It includes such stages of the product life cycle as: extraction of initial resources, transportation to the place of production, the process of production, use and disposal. Accordingly, we will calculate the so-called carbon footprint of production using one of the most common models - the Environmental Input - Output (EIO) Model [7, 8].

The EIO model is a "top-down" method. The methodological framework was developed in the 1970s. It is the fastest and easiest model which allows to calculate carbon footprint. To obtain calculations according to this model, it is necessary to use tabular values of the carbon emission rate (measured in kilograms of carbon dioxide) to establish the value of the carbon footprint of a product based on its price.

Approximate carbon footprint N for the calculated installation:

$$N = k \cdot Z = 50530 \text{ (tons of CO}_2\text{e)}$$

where $k=1.785$ tons of CO$_{2e}$/rub conversion factor according to [9], $Z=28\ 308$ rub - total cost of installation.

It should be noted, however, that the average carbon footprint in the Russian Federation per person per year is approximately 12 tonnes of CO$_{2e}$, while the global target to help contain climate change is 2 tonnes per person per year. It can be concluded that the issues of the need to create similar installations must be approached as responsibly as possible, not only from the point of view of efficient spending, but also from the point of view of the impact of the production of such a machine on the environment.

7. Conclusions

The graphs show that when the efficiency drops below 0.2, it makes no sense to increase the diameter of the air intake to increase the flow rate. It is also obvious that the flow rate entering the engine initially strongly depends on the diameter of the air intake, however, when the diameter is more than 0.5 m, the diameter of the inlet $d_0$.

We also see that the efficiency of the air intake decreases with increasing diameter. Low efficiency will require a higher specific impulse of the electric rocket motor.
From the calculations, a regularity is visible: the flow rate to the engine does not change at a constant ratio of the length of the air intake to the grid spacing. In other words, the ratio of the mesh spacing to the length of the air intake is the main parameter that determines its efficiency.

It is necessary to note the safety of testing the above-described installation in laboratory conditions, however, pay attention to the colossal carbon footprint from the use of this equipment.

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