Quantum Electronics **51** (7) 639 – 642 (2021)

LASER APPLICATIONS AND OTHER TOPICS IN QUANTUM ELECTRONICS

https://doi.org/10.1070/QEL17568

Possibility of increasing the efficiency of a laser jet engine due to the attachment of gas mass of shock waves

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Abstract. **Based on the results of studies of jet power propulsion systems with a pulsating working process, the thrust in which is significantly increased due to the gas mass attachment, and the analysis of the operation of a laser jet engine (LJE), we consider the possibility of such an effect in an LJE. The thrust characteristics of pulsating jet engines with the gas mass attachment are studied numerically and theoretically. Investigation of the effect of the attached mass of a gas or ablation products of the reflector material in the LJE is promising for optimising the gas-dynamic parameters that ensure the implementation of the maximum thrust efficiency of such an engine.**

Keywords: *gas-dynamic laser, laser jet engine, attached mass, resonator-thrust amplifier, pulsating working process.*

1. Introduction

One of the promising rocket engines of a new class is a laser jet engine (LJE) [1 – 5]. This is the engine of a spacecraft passing the initial part of the trajectory under the impact of a long series of laser pulses directed at it from the Earth's surface. The LJE exhibits significantly lower fuel consumption than traditional chemical-fuel engines. At the initial stage of the flight, atmospheric air is used as a working medium, and outside the atmosphere use is made of the products of ablation of the reflector material or the easily ionised substance contained in it.

To implement jet propulsion [5], the repetitively pulsed laser radiation is focused by a reflector located at the end-face of the rocket near its reflecting surface and produces periodically repeating laser sparks. Sparks generate shock waves in the air or in the ablation products of the reflector material, which transmit part of their momentum to it. The repetition rate of sparks is limited by the time of the gas change in the reflector and, depending on the rocket speed, can vary from hundreds of hertz to tens of kilohertz.

To increase the LJE thrust efficiency, Apollonov and Tishchenko [5] proposed a number of measures, in particular, the resonance merging of shock waves generated by an optical pulsating discharge. They showed that the specific thrust can also be increased by converting the radial component of the shock wave into a longitudinal one. As a result, the thrust can be increased fourfold.

It is known from the theory of jet propulsion that the thrust of an engine is determined from the Euler momentum equation. In a simplified form, without taking into account the input pulse (on the bench) and at equal flow rates of air and material vapours, the thrust for an air-jet engine is expressed as

$$R = Gc + (P_{\rm noz} - P_{\rm ext}),$$

where G is the gas consumption; c is the gas outflow rate; $P_{\rm noz}$ is the static pressure at the nozzle exit; and $P_{\rm ext}$ is the ambient pressure.

For a stationary flow, the specific thrust, i.e., the thrust referred to the air flow rate of 1 kg s^{-1}, is equal to the gas outflow rate c under the condition $P_{\rm noz} = P_{\rm ext}$.

The gas outflow rate c is mainly determined by the parameters of the thermodynamic cycle. The possibilities of increasing the rate relative to the achieved level are limited, for example, by its temperature dependence, which is proportional to $\sqrt{T}$, rather than to T, as in the case of G; with an increase in the outflow rate, the losses increase. To further increase the thrust efficiency, it is advisable to consider the results of work [5] using new data on the pulsating working process in jet engines.

2. Results

Below are the results of studies that show the possibility of increasing the thrust efficiency of jet engines due to the wave (shock) gas mass attachment in the pulsating working process, and an attempt is made to transfer these results to the physical picture of the processes occurring in the LJE.

1. An experimental pulsating air-jet engine (PAJE) made on the basis of a high-frequency constant-volume spool combustion chamber (CC) (V = const) of a new type [6, 7] was tested in the PJSC 'UEC-Saturn', both with and without an ejector thrust amplifier (ETA) (Fig.1).

The results of measurements of the thrust (by the thrust wall) of the engine without ETA and its calculations under the assumption of the quasi-stationary gas outflow process show that the measured thrust R approximately twice (depending on the spool rotation rate n) exceeds the calculated value (Fig. 2). This confirms the well-known theoretical study of a single cycle (one-dimensional expansion of detonation products – gas) [8], which demonstrated the possibility of increasing the momentum in the atmosphere by three times

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Received 19 April 2021; revision received 20 May 2021
Kvantovaya Elektronika **51** (7) 639 – 642 (2021)
Translated by M.A. Monastyrskiy

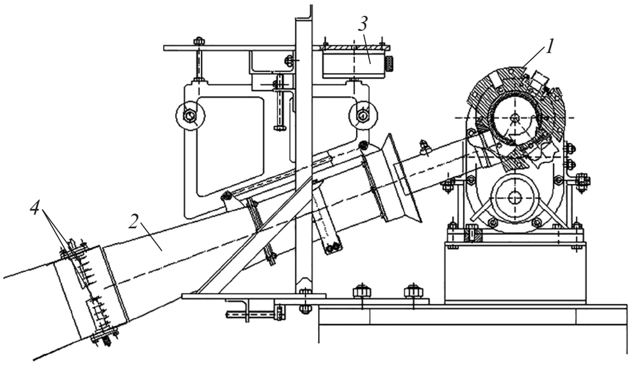

Figure 1. PAJE with a spool combustion chamber and an ejector thrust amplifier:
(*1*) PAJE; (*2*) ejector channel; (*3*) thrust measurement sensor; (*4*) sensors for measuring the total pressure and temperature of the gas.

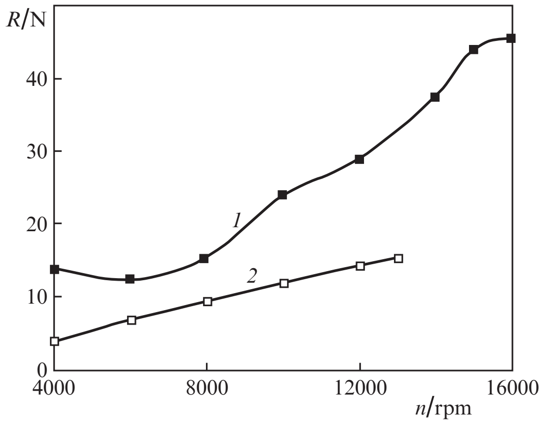

Figure 2. (*1*) Experimental and (*2*) calculated dependences of the PAJE thrust without ETA on the spool rotation rate.

compared to vacuum due to the mass attachment of atmospheric air by a shock wave.

Baum et al. [8] also showed that when a gas interacts with the atmosphere, an oscillatory process occurs, at certain moments of which the gas moves back to the source. This exhaust gas can become the attached mass for the next cycle. With the duty cycle of the operating pulsations being close to zero, it is possible to use part of the exhaust cyclic mass of the gas jet (its tail section, which has a lower rate than the front section) as the attached mass (Fig. 3).

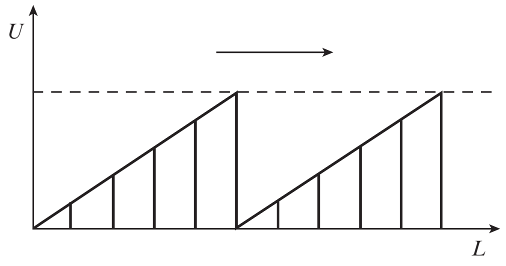

Figure 3. Typical distribution of the velocity U of the cyclic gas masses along the ejector channel length L.

The results of PAJE tests with ETA are presented in Figs 4–6 in the form of the dependences of the measured stresses on ETA, as well as of the dynamic head and pressure pulsations at the ejector channel output on the spool rotation rate n [6].

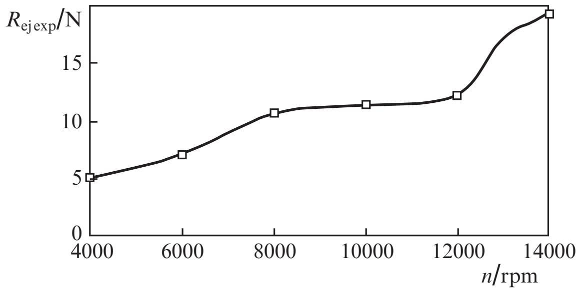

Figure 4. Dependence of the measured thrust in the ejector channel on the spool rotational rate.

It is of interest to vary the parameters in the range of spool rotation rates 12000–13000 rpm. When changing n by 8.3%, the thrust $R_{\rm ej\,exp}$ with ETA increased by 41% (Table 1). In this case, the velocity field at the ETA output changed dramatically – the flow rate in the near-wall region of the channel decreased. To explain this phenomenon, we calculated the change in thrust $R_{\rm ej\,calc}$ with ETA based on the flow parameters at its output, and analysed experimental and calculated results [9].

Table 1. Experimental and calculated values of the ETA thrust as functions of the spool rotational velocity.

n/rpm	$R_{\rm ej\,calc}$/N	$\rm R_{ej\,exp}$/N
12000	10.18	12.14
13000	10.23	17.15

Note. The measurements were performed using a strain-gauge force sensor (error of ±0.1%).

According to the calculated estimate, the thrust in the ejector channel increased by only 0.5% with an increase in n from 12000 to 13000 rpm, while the measured thrust increased by 41%. Let us consider the contradiction between the calculated and experimental data with allowance for the change in the velocity field in this range of the spool rotation rates.

A sharp decrease in the flow rate in the near-wall region of the ejector channel (Fig. 5) can be explained by its separation in the diffuse part of the channel. It is known [10] that the boundary layer separation is always associated with the formation of vortices as a result of the interaction of forward and reverse flows, and this is possible in the case of an oscillatory process. In this process, there can occur a mass attachment, which increases the thrust [8], i.e., the same air mass can form the thrust first as the active mass and then as the attached one. In this case, the kinetic energy (dynamic head) is converted into a momentum, which explains the contradiction between the measured thrust and its calculated estimate according to the dynamic head. It can be assumed that at $n =$ 12000 rpm there is a moderate gas mass attachment without separation of the flow, while at $n = 13000$ rpm the attachment is more intense, with separation of the flow and possibly a

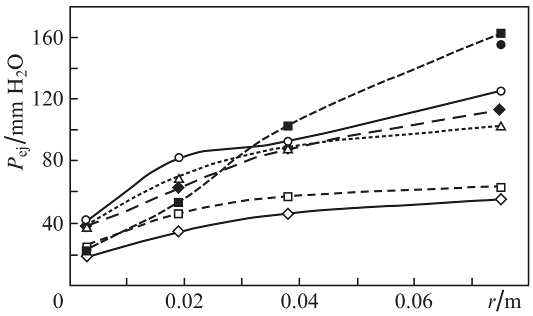

Figure 5. Distribution of the dynamic head measured by water piezometers in the radial direction at the ejector channel output at $n = 4000$ (◇), 6000 (□), 8000 (△), 10000 (○), 12000 (◆), 13000 (■), and 14000 rpm (●).

repeated attachment of the same mass of gas in a resonant oscillatory process (let us call it the attachment of the self-mass of gas).

To confirm the attachment of the self-mass of gas, as well as to exclude the possible attachment of the external mass, a cylindrical screen was installed at the ejector channel output (at a distance of 10–20 mm). Tests showed [9] that the thrust dynamics in the ejector channel did not change, and the thrust values with and without the screen did not differ much for the same pulsation frequencies. It is also characteristic that the dynamics of the amplitude pulsations ΔP measured at the ejector channel output by an LKh-610 sensor for $n >$ 12000 rpm coincides with the thrust dynamics measured in the ejector channel.

Note that the interaction of masses in a pulsating gas jet leads to shock losses. In this case, the higher the gas elasticity, the greater part of the gas kinetic energy is converted into a momentum as a result of the shock.

2. At the NASA Glenn Research Centre, during experimental studies of a pulsating ETA with a resonant device at the input [11], the efficiency factor of the ejection process was found to be at a level of 1.15, which contradicts the conservation laws. The reverse (backward) gas flow was observed at certain intervals. The authors of the study could not provide an explanation for this. The contradiction is resolved if the same mass of air is used first as the active mass, and then as the attached (not taken into account) mass in the oscillatory process.

3. At the Institute of Mechanics, Moscow State University [12], the specific (reduced to the working fluid consumption) thrust parameters of the pulsating process, organised on a setup based on a spherical resonator (Fig. 6), were 1.5–2 times higher than the values corresponding to the quasi-stationary calculation.

Similar experimental work carried out in 2004 at the A.M. Lyulka Scientific and Technical Research Centre once again confirmed these results. In addition, under certain operating conditions, a directly proportional dependence of the thrust on the air temperature at a constant pressure and a constant geometry of the flow section was revealed. Presumably, this can be explained by the fact that with an increase in temperature, the elasticity of the interacting cyclic gas masses increases (they are less deformed), and consequently, the impact losses decrease.

Computational studies of a spherical resonator-thrust amplifier [13] showed that in this case, an increase in thrust occurs mainly due to the attachment of the self-mass of gas in the high-frequency oscillatory process (Fig. 7).

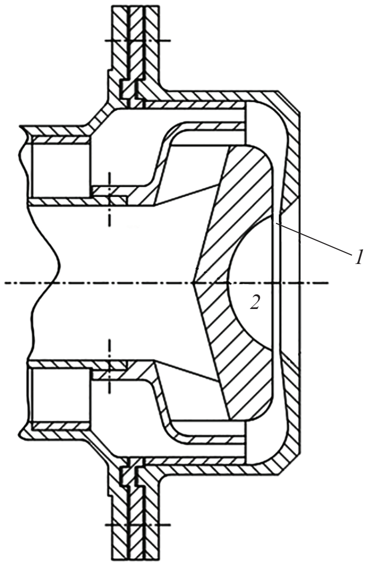

Figure 6. Spherical resonator: (*1*) nozzle critical section; (*2*) spherical cavity.

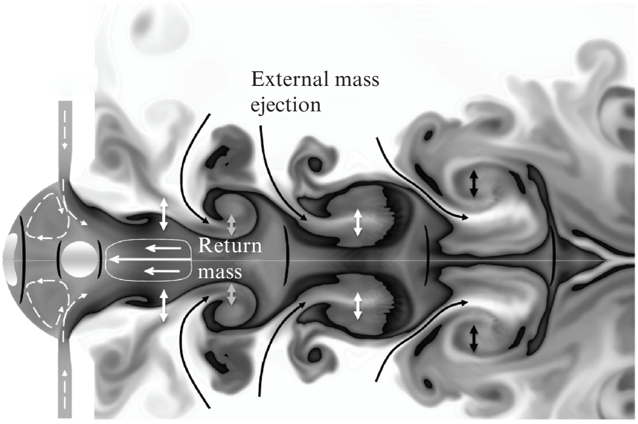

Figure 7. Flow visualisation in the resonator.

In addition, the change in the gas flow rate with distance from the resonator was investigated. From the analysis of the results obtained, it follows that, due to the attachment of gas masses, this rate is significantly lower than the calculated rate for a traditional stationary AJE flow. The flow rate in the critical section of the nozzle is also less than the calculated quasi-stationary rate due to the increased pressure in the spherical region of the resonator. Such a resonator being considered as a thrust amplifier can be used as an output device (nozzle) in jet engines.

4. To test the effect of increasing the momentum due to the interaction of only the gas self-masses in a pulsating jet engine in the conditions of space, an experimental installation with a spool device similar to a constant-volume combustion chamber was developed in relation to the VK-25 vacuum chamber ('NPO Mashinostroenie', Russia), providing a pressure of 0.001 MPa (technical vacuum) [14]. Figure 8 demonstrates the final test results, which have shown an excess of the measured specific thrust over the calculated one, thus indicating the attachment of the self-mass of gas. However, in experiments with the maximum degree $\pi_{noz} = 30$ of pressure reduc-

tion in the nozzle, a slight excess of the specific thrust over the calculated quasi-stationary thrust was observed. This can be explained by increased losses (both hydraulic and wave) due to the nonoptimal flow part design (spool–output device). The shock losses of the interacting cyclic gas masses also increase.

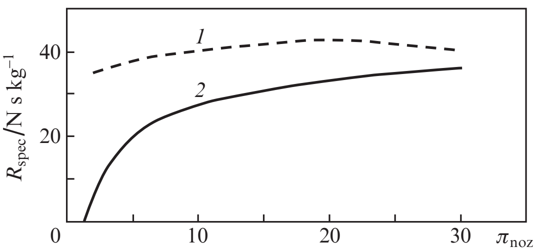

Figure 8. (*1*) Experimental and (*2*) calculated dependence of R_{spec} on π_{noz}.

3. Conclusions

The analysis of work [5] with allowance for the results of the above study of experimental propulsion systems has shown:

– from a physical point of view, the processes occurring in the reflector and installations, in terms of the interaction of gas masses or ablation products of the reflector material, can be close to the processes of shock-wave formation;

– a fourfold increase in the AJE thrust [5] can be additionally caused by the effective attachment of the gas mass (products of laser ablation of the reflector material) due to the resonance merging of shock waves;

– a computational study [5] was conducted without taking into account the effect of the attachment of gas masses (laser ablation products); making allowance for this effect will ensure, with optimal ratios of gas-dynamic parameters (frequency, duty cycle of working pulsations), the optimisation of the process of attachment of gas masses (laser ablation products) with maximum efficiency;

– in order to increase the AJE thrust due to the attachment of gas masses [5], it is advisable to conduct an additional study of AJE thrust characteristics associated with the gas flow rate responsible for the thrust (with an estimate of the gas outflow rate) using modern numerical methods; it is also necessary to evaluate the possibility of further optimisation of the parameters of the gas mass attachment process (laser ablation products).

We should also note that the CC (V = const) [15] designed at the PJSC ‘UEC-Saturn’ can be used in a ground-based laser installation to deliver pulses to the AJE. Its advanced efficiency, compared to the traditional CC (P = const), is provided by the increased gas temperature (10^3 K higher due to the short duration of exposure) and at least twice the rate of temperature drop in the nozzle [16].

This study is also of considerable interest from the point of view of evaluating the efficiency of laser methods for cleaning outer space from space debris and products of extraterrestrial origin [17].

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