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INTERACTION OF MASSES IN THE OPERATING PROCESS OF PULSE JET ENGINES AS A MEANS OF INCREASING THEIR THRUST EFFICIENCY

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Experimental and calculational-theoretical studies have been made of the operating process of pulse jet engines. With certain combinations of parameters of the operating pulsations, the interaction of cyclic gas masses among themselves or with the external medium (with and without the ejector channel alike) is possible, which provides an increase in the thrust efficiency of the engine.

When use is made of the ejector thrust amplifier based on the conventional air breathing engine with the fuel combustion at a constant pressure, the coefficient of amplification of the thrust is not high (the thrust increment is no more than 50%) because of a low level of the efficiency of the mixing process η, which is due to viscous mechanisms of the interaction of high- and low-head flows (Fig. 1) [1]. In this case, the higher the ejection coefficient μ, the lower the η. According to invention No. 314 [2], the thrust increment in a pulse ejector thrust amplifier can amount to 120–140%. The increase in the efficiency of the interaction of masses is here caused by a highly efficient nonviscous (wave) mechanism of energy transfer, which is the basic one. The effect was produced at the Moscow Aviation Institute (MAI) at an experimental setup at the operating pulsations with a frequency of 10 Hz and an off-duty factor of 80%.

At the open joint stock company of the Scientific-Production Association "Saturn," tests have been carried out of the pulse jet engine with the ejector thrust amplifier (Fig. 2) based on a high-frequency slide combustion chamber with a constant volume (V = const) [3]. The chamber volume was 310 cm^3. During the operation of the pulse jet engine, the following processes occurred sequentially as slide 3 was rotated: filling of the slide with air from inlet 4, fuel injection by atomizer 5, ignition by plug 6 set along the axis of rotation of the slide, combustion in a closed volume, gas efflux through the outlet facility (nozzle) 7, and blow-through. A part of the gases flows out through nozzle 10 in the slide, thus setting up a torque in it.

The thrust of the pulse jet engine with no ejector amplifier was measured using the well-known method resting on the principle of measuring the active force of a gas jet. For this, a thrust wall with a deflector and a force measuring device was placed at the engine outlet at a distance from the nozzle outlet equal to one and a half its diameter (Fig. 3). The deflector with an orifice for a guaranteed passage of the active jet provided its spreading normal to the direction of the thrust action. Since the maximum frequency of the operating pulsations f was limited by capabilities of the fuel equipment and was 100 Hz (the frequency of rotation of the slide was n = 6000 rpm), the measurement of the thrust and attendant gasdynamic phenomena was studied by supplying compressed air with a pressure of up to 0.28 MPa (with no fuel injection) to the inlet of the combustion chamber with V = const, which provided f = 250 Hz (n = 15,000 rpm).

The results of measurements of the thrust R_{exp} and of its calculations (based on in-engine parameters) (Fig 4) under the assumption of quasi-stationarity [4] of the efflux R_{c} showed that the forces on the wall are more than twice as large as calculated values of the thrust (depending on the operating conditions). This is because the pulse jet engine with the slide combustion chamber with V = const has an off-duty factor of the operating pulsations of ≈75%, and in between the supplies of gas jets the space behind the nozzle is filled with air from the surroundings (from the atmosphere), which, with the gas efflux, becomes an associated mass increasing the engine thrust. This is supported by the well-known calculational-theoretical investigation of a single cycle (of one-dimensional scattering of the detonation

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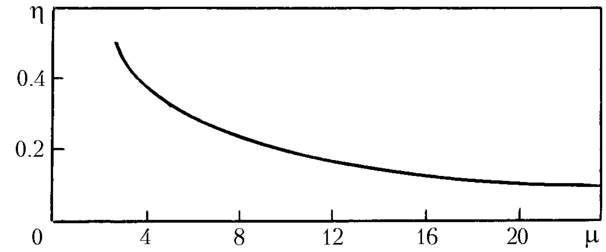


Fig. 1. Experimental dependence of the ejector efficiency η on the ejection coefficient μ.

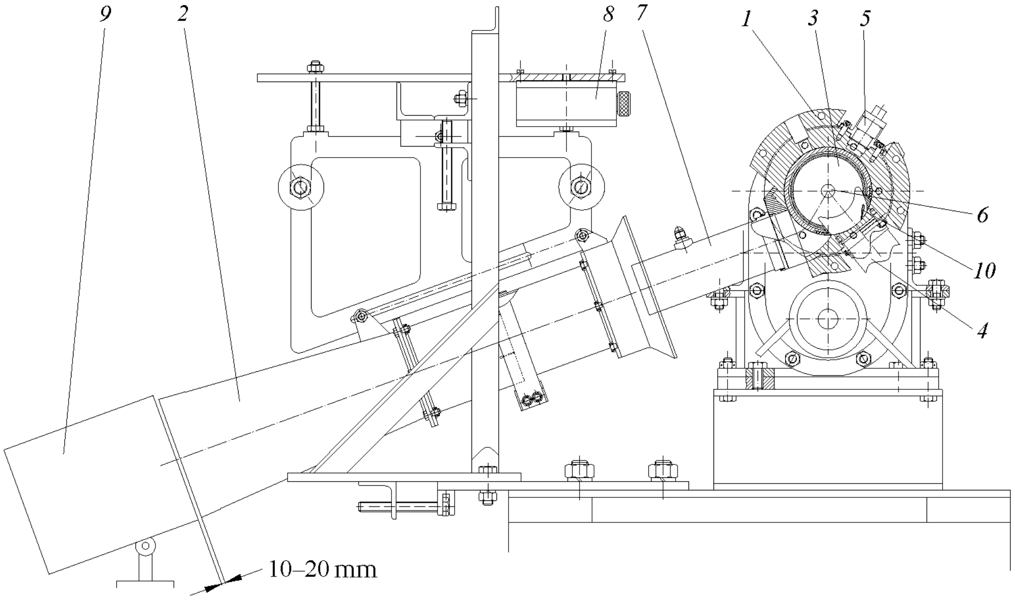


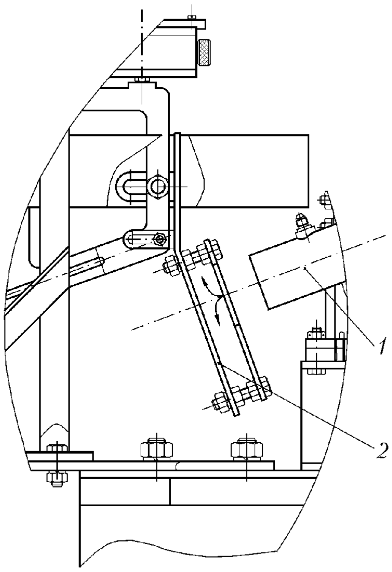
Fig. 2. Schematic of the pulse jet engine with the ejector thrust amplifier: 1) pulse jet engine; 2) ejector channel; 3) slide; 4) inlet; 5) fuel injector; 6) plug; 7) outlet facility; 8) force measuring element; 9) cylindrical screen; 10) nozzle in the slide.

products) [5], which demonstrated the possibility of a three-fold increase in the pulse in the atmosphere in comparison with the vacuum. Direct measurements of the jet thrust, performed on an experimental setup at the Moscow Aviation Institute with an off-duty factor of the operating pulsations of ≈80%, also indicated its appreciable excess over the calculated value [4].

The possibility of producing large forces on the wall by exposing it to a pulsating gas jet can be used as a new method of generating the lift.

Analysis of the phenomenon has also shown that the cyclic mass of an exhaust gas jet (of its tail having a lower velocity than that of the front) can partially be used as the associated mass when the off-duty factor of the operating pulsations is close to zero (Fig. 5).

The high efficiency of the pulsing operating process was demonstrated on a setup at the Institute of Mechanics of the Moscow State University [6], which has a higher frequency of the operating pulsations (10–20 kHz). However, when the thrust was matched to the measured air flow rate at the inlet, a contradiction with the laws of conservation was observed. It can be settled, assuming that exhaust gas jets have already been repeatedly used as the associated mass in producing the thrust. Investigations of one-dimensional gas flow with a detonation in the atmosphere [5] indicated that the gas interaction with air involves an oscillatory process, at a definite time of which the entire gas flows in reverse to the nozzle. Presumably, under specific conditions such an oscillatory process occurs also when the cyclic gas masses interact as a result of the difference in the velocities of their fronts and tails (Fig. 5).



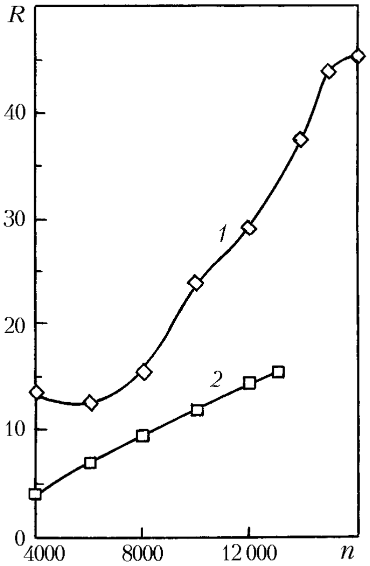


Fig. 3. Schematic of the nozzle of the pulse jet engine with a thrust wall: 1) nozzle; 2) thrust wall with a deflector.

Fig. 4. Thrust of the pulse jet engine as a function of frequency of rotation of the slide: 1) experimental data; 2) calculated results.

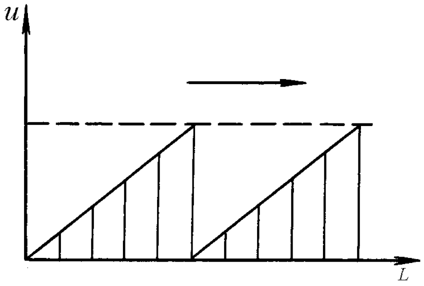


Fig. 5. Typical distribution of the velocity u along the length L of cyclic gas masses.

Then the exhaust gas jet can repeatedly participate as the associated mass in producing the thrust. In this case, the kinetic energy of the gas jet is transformed into a pulse. Thus, the actual gas flow producing the thrust is larger than the measured one, and the Euler law of conservation of momentum is not violated.

It can be supposed that this phenomenon was also the case with a pulse straight-through combustion chamber, which was studied experimentally at the Institute of Theoretical and Applied Mechanics of Siberian Branch of the Russian Academy of Sciences [7]. Here, the organization of pulsations (f = 1.5–2 kHz) in the combustion chamber using a special resonator resulted in an increase in the specific pulse by 1.5 times, which corresponds with about a twofold mass addition.

A calculational study has been carried out for the effect of a possible multiple use of the exhaust gas jet as the associated mass on the thrust efficiency η_{thr}, disregarding the influence of the mass flow of a fuel. Based on the known positions of the theory of the air breathing engine and ejector thrust amplifier, equations have been obtained for η_{thr} and the flight velocity V_0, at which the thrust of the pulse jet engine goes to zero:

$$\eta_{\text{thr}} = \frac{2}{1 + \frac{(1+\mu)\, u_{\text{c}}}{V_{\text{fl}}}}, \quad V_0 = (1+\mu)\, u_{\text{c}} \, .$$

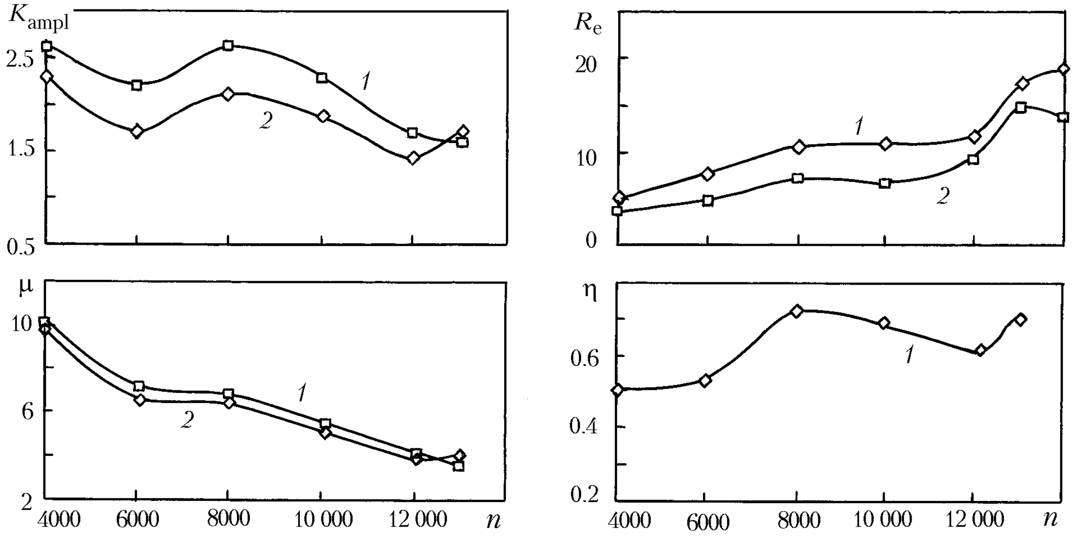


Fig. 6. Experimental characteristics of the ejector thrust amplifier; 1) $P_{\text{c.ch}}$ = 0.28; 2) 0.25 MPa.

Analysis of the equations indicates that, unlike the traditional air breathing engine, the flight velocity V_{fl} in the air breathing engine, as in the rocket engine, can be higher than the velocity of efflux from the nozzle u_{n}. Here, the assumption is made that, for pulsations with $f > 1.0$ and zero off-duty factor, u_{n} = const.

In investigations of the pulse jet engine with the ejector thrust amplifier, the force R_e, generated on the ejector, was determined. The dynamic head at the outlet from the ejector channel was measured by piezometers. Based on these measurements, we calculated the flow velocity at the outlet from the ejector u_2, the total flow rate μ, and the total thrust of the pulse jet engine with the ejector thrust amplifier. Geometric parameters of the ejector channels were "classical" (the length was equal to six diameters of the cylindrical part). The length of the cylindrical part was regulated. Channels of three standard sizes with diameters of 60, 80, and 100 mm were tested.

As shown above, the operation of the pulse jet engine with the ejector thrust amplifier can involve an attachment of the external additional mass; therefore, its actual specific thrust is dependent on parameters of the operating pulsations and surroundings. Consequently, to assess the degree of perfection of the pulse jet engines and compare their various types, it is advisable to take the "quasi-stationary" thrust as a datum one and, with respect to it, consider the actual thrust the pulse jet engine with and without the ejector channel alike in terms of the coefficient of amplification of the thrust $K_{\text{ampl}} = R_{\text{exp}}/R_{\text{c}}$. The ejection efficiency was evaluated using the known equation

$$\eta = \frac{K_{\text{ampl}}^2}{1+\mu}.$$

Figure 6 partially presents results for the channel with a diameter of 100 mm and a length of 500 mm, which provided a maximum thrust increment. Analysis of the tests demonstrated the following:

1. A shortening of the cylindrical part of the channel not only does not reduce the thrust (unlike a stationary ejector thrust amplifier) but even increases K_{ampl} by ≈5% (when it is demounted).

2. The maximum value $K_{\text{ampl}} = 2.6$ for the ejector thrust amplifier has been obtained under the following conditions: $P_{\text{c.ch}} = 0.28$ MPa and $n = 8000$ rpm. Here, $\eta = 0.92$ (not shown in Fig. 6), which hardly seems to be realistic for interacting gas flows. The overstating of η can probably be attributed to the fact that the pulsating jet in the ejector channel can experience the same transformations as those in the above case where the off-duty factor of the operating pulsations is close to zero. In this case, the actual air flow that produces the thrust can be higher than the measured one.

3. At frequencies of the operating pulsations above 200 Hz ($n \geq 12{,}000$ rpm), there is a sharp increase (by ≈1.5 times) in the force, which is measured in the ejector channel. In this case, the ejection coefficient is nearly invariable and the air flow increases by as little as ≈8%, which leads us to conclude that here also the same gas mass

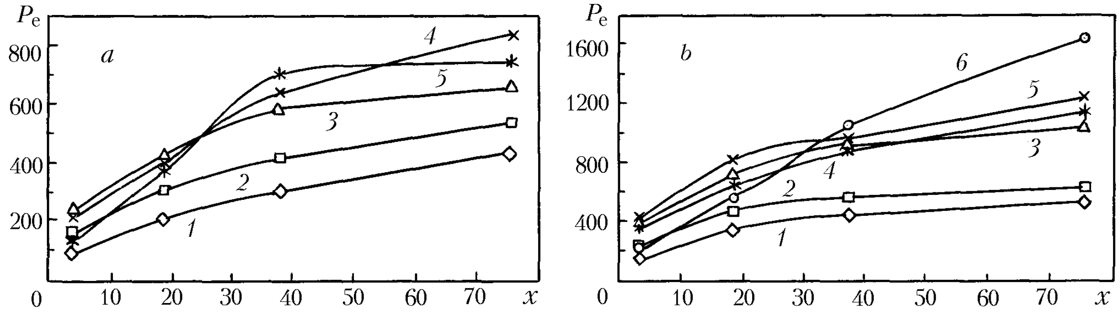


Fig. 7. Distribution of the dynamic head along the radius at the outlet of the ejector channel: 1) 4000; 2) 6000; 3) 8000; 4) 10,000; 5) 12,000; 6) 13,000 rpm. a) $P_{c.ch}$ = 0.25; b) 0.28 MPa.

can repeatedly participate in producing the thrust — initially as the active mass and thereafter as the associated one. The mass interaction can occur here in an oscillatory process, as noted above, with transformation of the kinetic energy into a pulse. In this case, the measured gas flow at the channel outlet will be smaller than the actual one that produces the thrust. Therefore, the estimation of the efficiency of the ejector thrust amplifier η based on the traditionally measured ejection coefficient μ_m can give an overstated value. In order to determine the actual value of the ejection coefficient μ_{act}, which allows for the repetitive use of the same gas mass in producing the trust, a simultaneous solution has been done of the known equations defining the operating process in the ejector thrust amplifier:

$$K_{ampl} = \sqrt{(1+\mu)\,\eta}\,, \quad \eta = (1+\mu)\frac{u_2^2}{u_1^2}\,.$$

Mathematical transformations yielded

$$\mu_{act} = K_{ampl}\frac{u_1}{u_2} - 1\,,$$

where u_1 has been calculated from in-engine parameters using the procedure from [4] under the assumption of quasi-stationarity of the efflux.

The processing of the test results using the equations obtained demonstrated an actual level of the attained maximum value of η = 0.73 (Fig. 6) and confirmed that μ_{act} can be higher than μ here.

The distortion of the velocity field at the outlet from the ejector channel indicates that the sharp decrease in the velocities on the periphery of the cross section (Fig. 7) is probably due to the separated flow near the diffuser walls, which, as is known, originates with a reverse flow in the boundary layer. This can serve as confirmation of the presence of the oscillatory process accompanied by the repetitive participation of the same gas mass in producing the thrust, which exactly causes a sharp amplification of R_e.

The study of the pulse jet engine carried out at the P. I. Baranov Central Scientific-Research Institute of Aircraft Engines [8] also demonstrated a high level of its characteristics at moderate pressures of the active jet.

CONCLUSIONS

1. In the pulse jet engine, a highly efficient attachment (increasing the thrust by more than a factor of two) of the associated mass can take place with and with no ejector thrust amplifier alike (in the presence of an off-duty factor in the operating pulsations).

2. The possibility of producing large forces on the wall by exposing it to a pulsating gas jet can be used as a new method of generating the lift.

3. At certain parameters of the pulsing operating process (specifically, at zero off-duty factor) in the jet engines, the exhaust gas jet can repeatedly be used as the associated mass for increasing the thrust efficiency by 1.5–2 times.

4. In the pulse jet engine, as in the rocket engine, the velocity of the gas efflux can be smaller than the flight velocity.

NOTATION

f, frequency of the operating pulsations, Hz; K_{ampl}, coefficient of amplification of the thrust; *L*, length of the cyclic mass of gas; *n*, frequency of rotation of the slide, rpm; *P*, pressure, Pa; $P_{\text{c.ch}}$, pressure in the combustion chamber, Pa; P_{e}, dynamic component of the total pressure at the outlet from the ejector channel, Pa; R_{c}, calculated thrust, N; R_{e}, force generated on the ejector, N; *R*, thrust, N; R_{exp}, experimental thrust, N; *u*, gas flow velocity, m/sec; u_{n}, velocity of efflux from the nozzle, m/sec; u_1, mean energy velocity of efflux of the active flow from the pulse jet engine, m/sec; u_2, flow velocity at the outlet from the ejector, m/sec; V_{fl}, flight velocity, m/sec; V_0, flight velocity at which the engine thrust becomes zero, m/sec; η, mixing efficiency; η_{thr}, thrust efficiency; μ, ejection coefficient; μ_{act}, actual ejection coefficient allowing for the repetitive use of the same gas mass in producing the thrust. Subscripts: act, actual; m, measured; c.ch, combustion chamber; fl, flight; c, calculated; *n*, nozzle; thr, thrust; ampl, amplification; e, ejector channel; exp, experimental.

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