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Base pressure oscillations and safety of load launching into orbit

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ABSTRACT

Physical details regarding base pressure low-frequency oscillations between rocket nozzles, their excitation and maintenance, are considered. Amplitude – frequency characteristics of these oscillations, as well as sequence of their type change, are studied. A single nozzle, a two-nozzle unit and a ring nozzle imitating multi-nozzle unit, are investigated in the present study.

1. Introduction

One of the key problems in spacecraft launching is the destruction risk of the carrier rocket due to unsteady interaction between supersonic jets emerging out of the multi-nozzle unit, and their affecting rocket base and the launch facility. This problem has been studied since 1950s, but some aspects are still unclear.

Physical details of base pressure low-frequency oscillations between rocket nozzles and their excitation and maintenance are considered in this study. Amplitude – frequency characteristics of these oscillations, as well as sequence of their type change, are studied. A single nozzle, a two-nozzle unit, and a ring nozzle imitating multi-nozzle unit, are studied. Nozzle units are installed inside a test channel having abrupt cross section expansion. The complex interaction between the exiting jet flows and the reverse flow produced upon their leaving the nozzles is studied.

It is demonstrated that the so-called expense mechanism underlies the oscillations. For some combinations of nozzle unit geometry and full pressure of the flow there is a misbalance between the two gas masses: one, which is ejected from a space near the rocket base, and a second, entering into this space from nozzle external flow. Results from experimental and computational investigation as reported here confirm this theory.

A model of the rocket base region, shown in Fig. 1, is composed of a high pressure reservoir (1) a nozzle (2) and a duct (channel) 3. The following geometrical parameters characterize the nozzle: the diameter of its critical cross-section (d_*), its exit cross-section diameter (d_a), the diameter of the duct (tube) section (d_t), the nozzle throat angle (θ_a), and the duct (tube) length (l_t). Amplitude – frequency dependencies for base pressure (P_b) oscillations are analyzed. Flow regimes, types of shock-wave structure oscillations and laws of their change due to full pressure (P_O) variation are also studied here.

The very first experimental studies demonstrated that the unsteady effects associated with base pressure oscillations have significant influence on the vehicle supersonic flight. Meaningful changes in the load direction are a serious menace in supersonic vehicle constructions.

The loads are especially large at rocket engine jet interaction with launch facility surface, walls of launch container, jet – jet and jet – rocket base interaction. Typical steady and unsteady (oscillatory) flow regimes are shown in Fig. 2, above and below, correspondingly. Other facilities where shock-wave structure oscillations are typical also exist in spacecraft (ejector nozzles, for example). The problem of separated supersonic flow and associated base pressure oscillations is common for all of them.

1.1. *Background and history of studies of flows at the base region and base pressure oscillations*

Among other problems of jet – obstacle interaction, problem of supersonic jet flow in channels with abrupt expansion has its separate place. Such flows, similar to reverse step flow, are realized in various engineering facilities (for example, in tubes of launch facilities, nozzles with abrupt steps, diffusers of the test benches for high altitude imitation, metallurgical furnaces, gas fittings and pipelines in chemical industry.

A large number of studies are dedicated to interior separated flows

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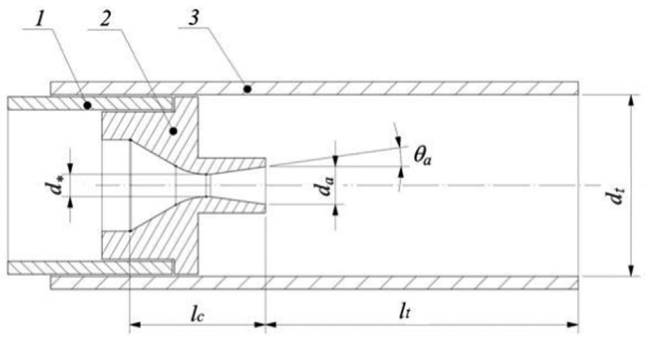

Fig. 1. The geometry of the duct with abrupt expansion: 1 – reservoir, 2 – supersonic nozzle, 3 – cylindrical tube. Here l_c is the nozzle length.

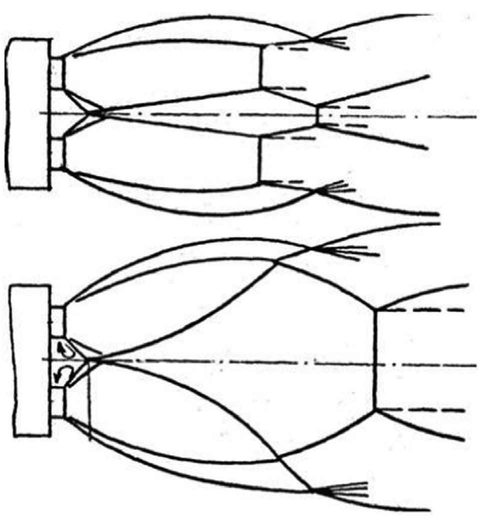

Fig. 2. Interaction of jet flows out of nozzle unit; for the steady regime (above) and oscillatory (below).

and associated base pressure variation. Nusselt was named as the first researcher of flows experiencing abrupt expansion [1]; he experimented with transonic jet flows out of the narrowing conical nozzles and compared his results with one-dimensional flow theory.

Numerous publications on jet flows at the base region, especially involving base pressure problems, appeared shortly after WWII [2–9]. Three steady regimes of ejector flow (mixed, transitional, and supersonic one) were discovered in conical and shaped nozzles with exit Mach number M_a=1.836 [2]. A series of shadow (Schlieren) photos of the wave structures illustrated the flow regimes for the first time in that study. They demonstrated that as the reservoir pressure ahead of the nozzle increases, the base pressure initially decreases, and thereafter increases linearly after having some minimal value.

Attempts to achieve a reliable scheme of separating supersonic flow in the duct and to derive some numerical relations for the base pressure were undertaken in [10–12]. These studies contain research of sonic and supersonic jet flows in channels with abrupt expansion. Either shadowgraph photos showing the wave structure, or interferograms indicating various phases/regions of stream formation, are presented there. To define the range of self-oscillation existence and to exclude these self-oscillations was the goal of studies conducted at the beginning of the 1950s. But sometimes (for example, in metallurgy and for the hardening of materials) powerful low-frequency oscillations were useful and were applied to industrial practice.

More profound, detailed and comprehensive studies were provided later [13,14]. Base pressure – reservoir full pressure dependence $P_b(P_O)$ was achieved for the axisymmetric duct of limited length [11]. Typical base pressure variations at the sonic nozzle flow were discovered, as well as hysteresis phenomena of shock-wave structure at

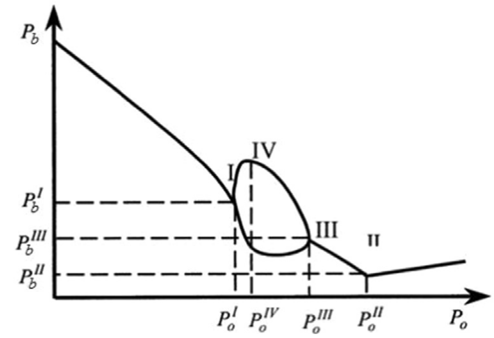

Fig. 3. Typical changes in the base pressure upon changes in the reservoir total pressure. Point I corresponds to the starting of self-oscillations, point II – to minimal base pressure, point III – to the end of oscillations, point IV – to maximum oscillations amplitude.

increase or decrease in the reservoir pressure. Low-frequency oscillations of the base pressure are discovered in [13]. As a result, the conception of $p_b(p_O)$ dependence became basically modern (Fig. 3).

Outstanding studies of round and ring jet flows inside plane and axisymmetric ducts were provided in 1968–1980 [12–20]. Oscillatory base pressure regimes and shock-wave structure shift were discovered there experimentally using the fringe patterns in plane transparent channels and inertialess pressure sensors. W.M. Jungowski introduced the conception of "oscillations of the steady shocks" in his studies [12,13,21–24].

Non-classified publications on the topic appeared in the Soviet Union sometime later. But it does not mean absence of studies. Self-oscillatory interactions of supersonic jet flows faced with obstacles (parallel, normal to jet symmetry axis or inclined ones) were conducted in various organizations (TsAGI, Baltic State Technical University, Institute of Theoretical and Applied Mechanics of the Siberian Branch of the RAS, etc.). Some books (for example, [25,26]) and numerous papers were published.

O.N. Zasukhin [27] studied the flow pulsations in various nozzle sets. He confirmed W.M. Jungowski's conclusion about the determining influence of shock-wave structure pulsations on the acoustic noise formation. Above it, so called flow rate mechanism of oscillations was stated, and it was proven that the acoustic feedback is subsidiary. This fact was substantiated by experimental studies of jet flow interaction with normal plane obstacles (Fig. 4).

Numerous theoretical, experimental and numerical studies performed in 1970s-1990s [28–32] had shown that the triple configuration of the shocks (at point T, Fig. 4) becomes unsteady and oscillates intensively between the nozzle and the obstacle. These oscillations occur at some specific jet flow parameters and distances between the

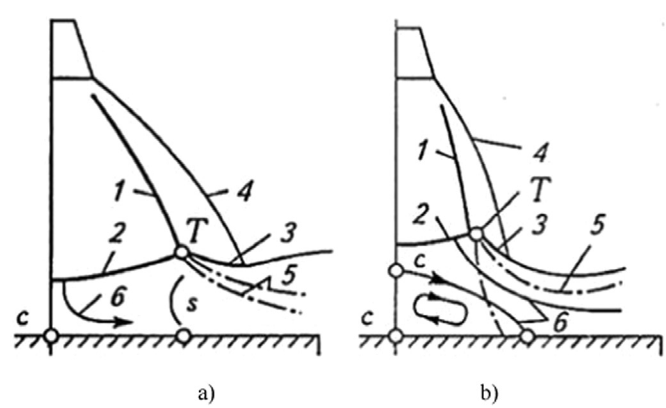

Fig. 4. Shock-wave structure of the supersonic jet at its interaction with a plane infinite obstacle: a) steady flow regime; b) flow with the central circulation zone; 1) "suspended" oblique shock; 2) central shock (Mach stem); 3) reflected shock; 4) jet boundary; 5) slipstream (mixing layer); 6) any streamline; s is sonic line; c is flow stagnation point.