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Self-Oscillation of Shock Wave Structures

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ABSTRACT

The oscillations of shock wave structures have been reviewed. The particular attention has been brought to oscillations related to the base pressure problem as to the most important problem of the flow over the bottom parts of aircrafts. Landmark research on problem of base drag, as well as of oscillation occurrence at bottom part of nozzle blocks and channels are given. The problem of supersonic air inleak onto the obstruction is reviewed. Great attention is paid to results of experimental research and to analysis of calculation issues. The mechanisms of feedback occurrence and self-oscillation maintenance are described. Shock wave oscillation arises during the supersonic flow collision with obstruction. It is a result of complex interaction between forces of viscous friction in mixing layers and shock wave structure elements transformation. Due to its relation to filling and emptying of flow regions with stagnation and low velocity, this mechanism was called “the consumption mechanism”. Acoustic feedback has an impact on the amplitude-frequency characteristics of oscillation, but do not cause them.

KEYWORDS
Gas-dynamic discontinuity; shock wave structure; oscillation of shock wave structures; base pressure

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Introduction

The first experimental researches have shown considerable influence of shock wave-related non-stationary effects on supersonic flows around an aircraft. High value alternating load posed serious threat to integrity of a supersonic aircraft.

They appear to be substantial during interaction between rocket engine’s jets and a launch pad, launcher’s walls, and also between themselves and with the base area of a rocket (Fig 1. top – stationary mode, bottom – oscillatory mode). There are other examples of flows which have oscillation of shock wave structures in canals and planes: inner bays of aircraft’s weaponry, supersonic afterburners, ejection nozzles etc. They all share the same technical problem - separated supersonic flow and base flow related to it.

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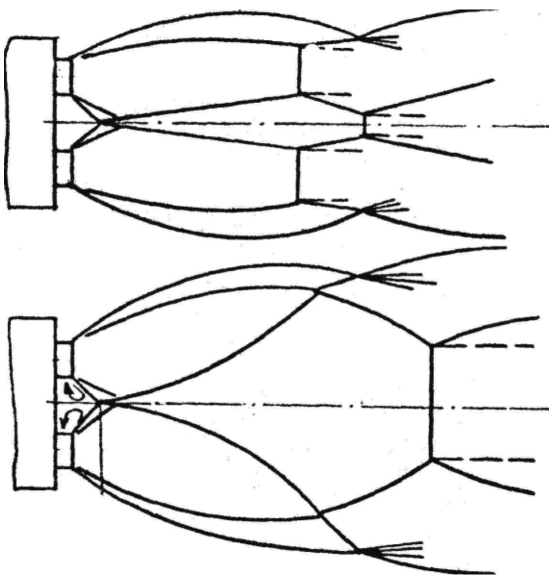


Figure 1. Interaction between flows outgoing from nozzle block

Starting with works of E. Mach (1878), the research on supersonic flows are being conducted by scientists from various countries, however numerous phenomena occurring in them have yet not been revealed. One of such phenomenon is an appearance of self-oscillation during interaction of a flow with an obstacle.

Since the end of 50's of past century the self-oscillating interaction mode of supersonic flows with obstacles have been actively studied by teams that belong to various aerodynamics schools of Russia (Central Aerohydrodynamic Institute, BSTU "Voenmeh", ITAM SB RAS, et al.). Based on numerous theoretical, experimental and computational researches, various hypotheses about origin of this mode and mechanisms of its maintenance are suggested. There are monographs (Zapryagaev, Uskov & Gaponov, 2000) and numerous articles published, dozens of theses defended on this subject. However, many aspects of phenomena are still unclear to this day and require addition research.

At the beginning of 50's the aim of research was to determine the diapason of oscillation's existence and to eliminate it, or at least to lower their amplitude to acceptable level. However, such oscillation can be beneficial in numerous problems, for example in metallurgy during mixing of molten mass, as well as during material hardening. Powerful low frequency oscillations are beneficial and used during technological process.

When designing an aircraft and spacecraft transport systems, one of the most important problems is a problem of reducing the base drag. To model the flow near base area of an aircraft and inside engine nozzles, the flow inside a cylindrical canal with sudden expansion of cross-section surface has been used as a model for at least past sixty years. For example, a gas flowing through a supersonic nozzle with cylindrical attachment (Fig. 2).

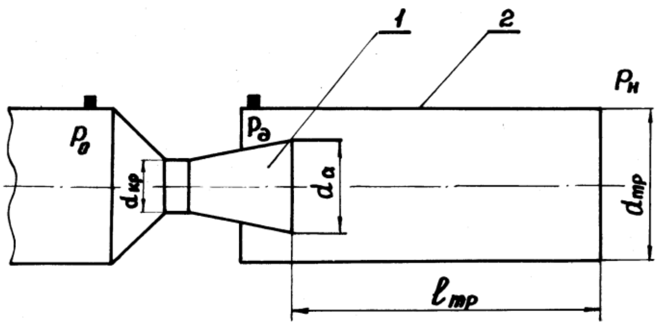


Figure 2. The geometry of a canal with sudden expansion

Fig. 2 shows parameters that fully describe geometry of the nozzle 1 and of the canal 2. They are d_{kp}– nozzle cross-section diameter, d_a – diameter of nozzle's exhaust section, θ_a- angle of half-open nozzle at its cut section, d_{mp} – canal's diameter, l_{mp} - canal's length.

Amongst many problems of aerodynamics associated with interaction of supersonic flows with obstacle, the problem of flow in canals with sudden cross-section expansion is a special case, related to separated flows, and the problem itself can be considered classical. Such flows are similar to flow around reciprocal step, and appear inside various technical devices such as: launcher's barrel, nozzle with discontinuous generating line, diffusers for experimental stands that imitate high altitude conditions, tuyere and pumps of metallurgy furnaces, gas valves and pipe systems of chemical factories.

The more turbulent separation is studied, as with any other natural phenomenon, the more complex by its forms and properties it appears. However, from practical point of view, the certain progress has been achieved, which allows to predict presence and properties of a developed separation and take them into account while designing technical devices. The variability of real separated turbulent flows, their complex physical nature and lack of general theory leads to necessity of using a physical experiment in combination with approximate calculations andanalytical research, even more than in other areas of gas-dynamics.

There are many works on research of internal gas flow and base pressure related to it. The book called «Basics of gas dynamics» (Crocco, 1958) names Nusselt the first to study flows with sudden expansions. he carried out experiments with transonic jets, that come out of convergent nozzles. He compared the acquired results with calculations based on one-dimensional theory. The book also describes ejection systems without secondary flow with cylindrical mixing chambers, which are similar to a canal shown on Fig. 2. Using the equation of energy conservation and taking into account the friction on the surface of mixing chamber, the existence range of solutions of the equations for calculating relative base pressure have been found.

Literature review

The needs of rapidly developing aviation technology, and later - rocket technology, have been stimulating the research of internal detached flows. Such researches have been carried out in many countries, and around same time the publications have appeared describing the research of processes occurring inside channels with supersonic outflow from nozzles and nozzle sets with base as well as specifics on base pressure variability. For instance, works of E. P. Neumann & F. Lustwerk (1949), K. Karashima (1961), The work of W. L. Chow (1959) is one of the most important fundamental works that deal with the problem of base pressure. In Soviet Union freely available publications have appeared later, which doesn't mean absence research on this direction.

The one-dimensional approach was used by I. P. Ginzburg (1958) to determine the losses of full base pressure the nozzle in a flow outgoing from a nozzle and interacting with walls of cylindrical canal. Referencing R. S. Wick's (1953) experimental data on base pressure, the coefficient fortotal pressure loss have been determined.

J. Fabri & R. Siestrunck (1958) by using conical and divergent shaped nozzles with M_a = 1.836 in their research, discovered the existence of three stationary modes of ejector: mixed, transient and supersonic (Fig. 3).

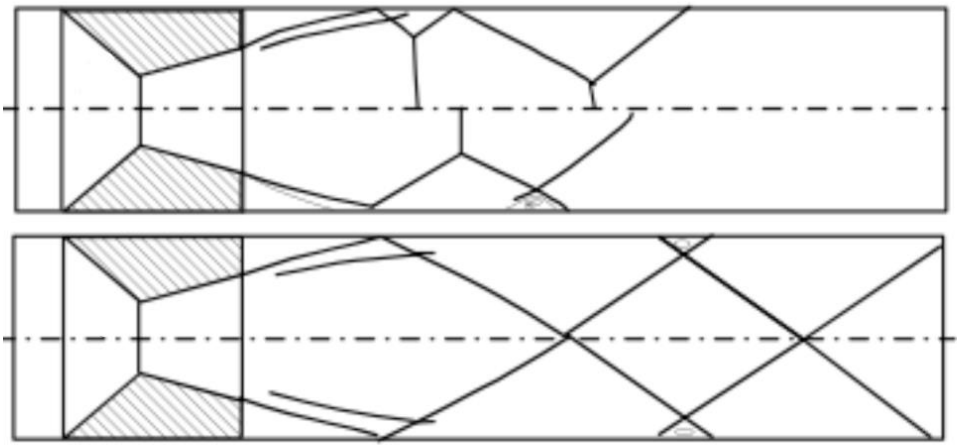


Figure 3. Shock wave structure inside a canal with sudden expansion on different ejection modes

They showed that with an increase of total pressure before the nozzle, the base pressure decreases at first, but after reaching some minimal value it increases linearly. To physically illustrate the flow modes in the work, the series of schlieren photos of wave structure was demonstrated for the first time. The photos were acquired using a flat apparatus with transparent walls and were corresponding to various phases of supersonic flow formation.

The later experimental research of detached supersonic flows has lead to deeper and broader study of this phenomenon. The main goal was still to acquire reliable image of supersonic flow inside the channel and quantitative dependences on base pressure. The example of such research are works of J. S. Anderson & T. J. Williams (1968), B. W. Martin & P. J. Baker (1963) and W. M. Jungowski (1969). All of these works contain research of sonic and supersonic flows inside channels with sudden expansion and visualization of wave structure when using flat apparatus with transparent walls. The works present either schlieren photos or interferograms corresponding to different phases of supersonic flow formation inside the canal.

The research of base pressure P_∂ that depends on total pressure P_0 for a canal of limited length is provided (Martin & Baker, 1963). The researches shows the existence of typical dependencies of sonic nozzle's base pressure variation and of hysteresis phenomena with wave structure transformation if total pressure P_0 increases or decreases.

In 1969, Jungowski's study the low frequency oscillation of base pressure has been found, as a result of what the understanding of the dependence of base pressure on total pressure before nozzle acquired a modern image (Fig. 4). The abovementioned works are part of wide research on detached flows, and were referenced in monographs of A. M. Sizov (1987).

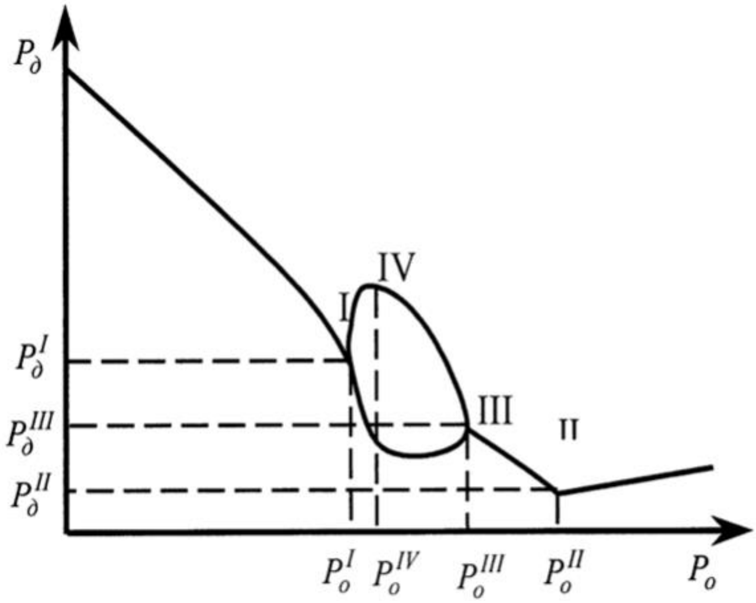


Figure 4. A typical graph of base pressure's dependency on total pressure before nozzle (I - oscillation start, II -minimal base pressure, III -oscillation end, IV- oscillation maximum amplitude)

The aim of this work is to review the history of study in the sphere of base pressure oscillation and shock wave structures. The main attention is paid to the analysis of so-called consumption oscillation, as well as to the study of last decisions and forecasts for the future. The acoustic oscillation, interaction between vortexes and shock waves, and problems of corrugation instability of shock waves are not discussed.

Method

The paper is used analysis of leading scientists from both domestic and foreign schools, who were engaged in issues of this study. The paper is widely used comparative analysis.

Data, Analysis, and Results

A sufficient review of this problem is shown in works of P.V. Bulat & N.V. Prodan (2013). A review of existing models for shock wave structure oscillation associated with base pressure and sudden expansion of supersonic flow is present in a work (Bulat & Prodan, 2013).

A complex of researches on flows inside flat and axially symmetrical canals for circular and annual jets have been carried out by W.M. Jungowski and colleagues during 1968 to 1980 (Meier et al., 1980). The results of visual analysis of flows inside transparent flat canals using interferograms and measurements using pressure sensors allowed him to discover the existence of oscillation modes of base pressure and wave structure transformation. W. M. Jungowski was first to introduce term "shock oscillation". In his works he paid a great attention to acoustic aspects.

O.N. Zasukhin carried out a series of experiments to study pulsations in various nozzle setups (Bulat, Zasukhin & Uskov, 1990). The acquired results prove the conclusion made by W. M. Jungowski about defining influence of shock wave oscillation on formation of acoustic radiation (Bulat, Zasukhin & Uskov, 2012). In addition, the so-called consumption mechanism of oscillation cycle maintenance was proven, and it was shown that acoustic feedback is of secondary significance.

The experimental data on amplitude-frequency characteristics of SWS oscillation, level of acoustic radiation, oscillation's formation and maintenance mechanism, methods of shock's noise damping, and fine structure of oscillation cycle, has been generalized by P.V. Bulat and O.N. Zasukhin in 2000s (Bulat, Zasukhin & Uskov, 2012).

One of the most complex computational problems is the calculation of SWS oscillation that interacts with turbulent viscous flow.

G. Grabitz (1979) made an attempt to calculate the oscillation mode's frequency using his assumed mathematical model with various laws of feedback between external and base pressure during oscillation mode.

The results of said calculation were in satisfactory agreement with experimental results, but only in unique cases.

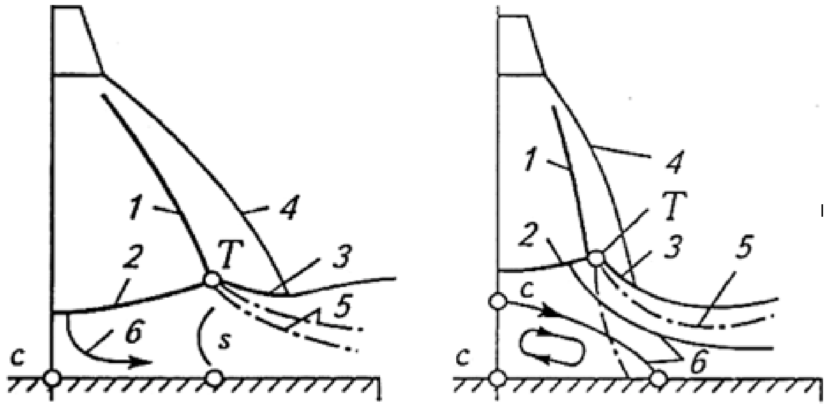
The direct numerical calculation of SWS oscillation using Navier–Stokes equation with averaged time values, closed via various turbulence models, often encounters methodological difficulties. Nonetheless, in series of practically important cases when oscillation mode's frequency significantly differs from typical frequency of converging vortexes inside turbulent flows the direct approach can be used, as shown in works by P.V. Bulat (2013).

All other cases require either solving complete Navier–Stokes equations or developing calculation method with explicit emphasis on discontinuity's and waves (Bulat & Bulat, 2013). There are numerous difficulties, associated with subsonic flow region, when implementing calculation method of supersonic flow with explicit emphasis on discontinuities. In addition, it is required to have at least approximate data on structure of the studied flow and the work on this subject is far from being done.

SWS oscillation of supersonic jet when colliding with obstracle perpendicular to its axis

During rocket's launch the interaction between SWS of supersonic jet and flat obstacle occurs (Fig. 5). Such SWS also occurs in following technological processes: shock metal hardening, coating, and molten mass oxygenation inside open hearth furnace.

The presence of jet, orthogonal to flat obstacle's axis, inside first barrel leads to triple configuration T being shifted closer to the nozzle. (Fig. 5) (Ginzburg, Sokolov & Uskov, 1976).



a) b)

Figure 5. Shock wave pattern of interaction between supersonic jet's SWS and flat limitless obstacle (a - stationary flow regime; b - flow with a central circulation zone; 1 - suspended shock; 2 - central shock; 3 - reflected shock; 4 - jet's edge; 5 - mixing zone; 6 - flow line; s - sonic line; c - point of flow deceleration)

Numerous theoretical, experimental and numerical researches were carried out during 70's to 90's of XX century (Ginzburg, Sokolov & Uskov, 1976). They showed that under certain combination of parameters of outflow and nozzle withdrawal from an obstacle the triple configuration of shock wave (T on Fig. 5) becomes unstable and exhibits strong oscillation between nozzle and obstacle.

Compression and rarefaction waves tend to appear inside of shock layer, and in some cases shock waves appear as well, which is proven by experimental data and numerical calculations. In work by V.G. Semiletenko, B.N. Sobkolov & V.N. Uskov (1972) the one-dimensional model of oscillation cycle is suggested (Fig. 6).

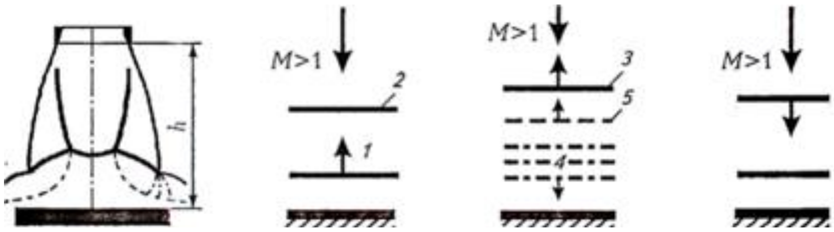


Figure 6. A diagram of shock wave self-oscillation process

The model is based on internal feedback mechanism, which is implemented by interaction between waves and discontinuities. During the initial moment of jet outflow from the nozzle, located at distance h from the obstruction, the central shock is stationary. Shock wave 1 forms as a result of flow choking behind central compression shock, by peripheral flow. Wave 1 moves from obstacle by subsonic flow, reaches resting central shock 2, and interacts with it. As the result of such interference, the central shock transforms into shock wave 3, which is counter-propagated to supersonic flow and directed towards nozzle. The reflected expansion wave 4 propagates towards an obstacle. Contact discontinuity 5 that separates flows behinds shock wave 3 and rarefaction wave 4, is able to move towards the nozzle. Wave 4 reflects from obstruction in form of rarefaction wave, which moves towards the nozzle, and after refraction at contact discontinuity 5 closes in on shock wave 3. As a result of interference the shock wave 3 becomes adrift, and relative to supersonic flowm moves towards the obstacle and interacts with it. The interaction between shock wave and obstacle results into increase of pressure on its surface, which removes the “blockade” of central flow, and it leaves the shock layer. And then the cycle repeats.

Along with this scheme the scheme of feedback is suggested. It is performed through external medium (external feedback) via disturbances, caused by oscillations traveling from obstruction towards nozzle across mixing layer and back across jet’s edge. Presence of such feedback is proven by placement of acoustic shields outside of the nozzle. Such shields change oscillation’s amplitude-frequency characteristics.

Years long discussions of feedback mechanisms, which were reflected in publications, allowed making a conclusion of their involvement in self-oscillation mode with the prevailing role of internal feedback. The last statement is proven by results acquired from experimental research on self-oscillation mode of jet flowing onto an obstacle with supersonic satellite flow (Gorshkov, Uskov & Ushakov, 1991). Such flow, with an exception of external feedback, does not interfere with the internal feedback.

Discussion

The oscillation described above was studied using numerical methods: firtst using model of an ideal gas, and then using model of viscous gas. It should be noted, that the most interesting work among researches within models of an ideal gas is a work of B.Sh. Albazarov (1991), which allowed to allocate and register shock wave structures movements inside the shock layer. A special notice deserves a series of works by A.V. Savin & E.I. Sokolov (1998), that is based on numerical calculation of viscous three-dimensional Navier-Stokes equations. It is shown that within Navier-Stkoes equations model averaged by Reynolds, the nonphysical solution – a self-oscillation in locations where they are not displayed by the experiment sometimes occur.

Amplitude-frequency characteristic of oscillations are strongly affected by obstacle size. There are also silent region” for which self-oscillations modes almost disappear. Thus, the self-oscillation mode of interaction between supersonic jet and obstacle is caused by irregular spread of jet’s parameter and is based on geometrical and aerodynamical nozzle parameter, obstacle size and its distance from nozzle.

Conclusion

Shock wave structures’ oscillation during interaction between supersonic flows with an obstacle, mixing and boundary layers are amongst most complex aerodynamic phenomena. This phenomenon is difficult to calculate. However, using special computational methods, it’s possible to perform calculation in a case when wave numbers of oscillation and turbulence differ significantly by an order of magnitude. Of course, results must be checked via experiment.

Thorough experimental research of supersonic wave’s flow into the canal, flow onto axially perpendicular obstruction, as well as in presence of satellite supersonic flow, has demonstrated that oscillation maintenance is defined by consumption mechanism, associated with filling and emptying of stagnant flow regions, choked by SWS. Acoustic feedback doesn't play a significant role, but with absence of satellite supersonic flow does influence the properties of oscillation.

The internal reconstruction of shock wave structure is responsible for arising and destruction of stagnant internal flows, inside which gas circulates with at low velocity. The gas is ejected from those areas by mixing layers, and is filled as result of interaction between said layers and elements of shock wave structure.

Thus, shock wave oscillation, during supersonic flow collision with obstruction, arises as a result of complex interaction between forces of viscous friction in mixing layers and of shock wave structure elements transformation. This mechanism was called "consumption mechanism", because it's related with filling and emptying of stagnant flow regions with low velocity. Acoustic feedback influences oscillation's amplitude-frequency characteristics, but is not their cause.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Albazarov, B. Sh. (1991) *Numerical simulation of the interaction of a supersonic jet with an obstacle*: PhD thesis, Krasnoyarsk, Russia. 16p.

Anderson, J. S. & Williams, T. J. (1968) Base pressure and noise produced by the abrupt expansion of air in a cylindrical duct. *Journal of Mechanical Engineering Science, 10(3),* 262–268.

Bulat, M. P. & Bulat, P. V. (2013) Comparison of turbulence models in the calculation of supersonic separated flows. *World Applied Sciences Journal, 27(10),* 1263–66.

Bulat, P. V. & Prodan, N. V. (2013) On the low-frequency oscillations of expenditure base pressure. *Fundamental Research, 14(3),* 545-549.

Bulat, P. V., Zasukhin, O. N. & Uskov, V. N. (1990) Mechanisms of non-stationary processes in a channel with a sudden expansion. *Proceedings of XV All-Union seminar on gas jet.* 21p.

Bulat, P. V., Zasukhin, O. N. & Uskov, V. N. (2012) On classification of flow regimes in a channel with sudden expansion. *Thermophysics and Aeromechanics, 19(2),* 233-246.

Chow, W. L. (1959) On the base pressure resulting from the Interaction if a supersonic external stream with a sonic or subsonic jet. *J. Ae. Sci., 26*, 176-186.

Crocco, L. (1958) One-dimensional treatment of steady gas dynamics. *Fundamentals of gas dynamics, 3*, 259-274.

Fabri, J. & Siestrunck, R. (1958) *Supersonic air ejectors. Advances in applied mechanics.* New York: Academic Press. 34p.

Ginzburg, I. P. (1958) *Applied Hydrodynamics.* Leningrad: Leningrad State University press. 325p.

Ginzburg, I. P., Sokolov, E. I. & Uskov, V. N. (1976) Types of wave structure in the interaction of a convergent jet with an infinite two-dimensional obstruction. *Journal of Applied Mechanics and Technical Physics, 17(1),* 35-39.

Gorshkov, G. F., Uskov & V. N. & Ushakov, A. P. (1991) Oscillatory interaction between an underexpanded jet and an obstacle in the presence of a supersonic sheathed flow. *Journal of Applied Mechanics and Technical Physics, 32(4),* 512-518.

Grabitz, G. (1979) Model calculations of self-excited oscillations in transonic flow in a duct with an abrupt enlargement. *Sixth International Conference on Numerical Methods in Fluid Dynamics Lecture Notes in Physics,* 90, 268-273.

Jungowski, W. M. (1969) On the flow in a sudden enlargement of a duct. *Fluid Dynamics Transactions, 4*, 231-241.

Karashima, K. (1961) Base pressure on two-dimensional blunt-trailing-edge wings at supersonic velocity. *University of Tokyo, Aero, Research Institute Report, 368(27),* 8-11.

Mach, E. Uber den Verlauf von Funkenwellen in der Ebene und im Raume. *Sitzungsbr Akad Wien, 78*, 819-838.

Martin, B. W. & Baker, P. J. (1963) Experiments on a supersonic parallel diffuser. *Journal of Mechanical Engineering Science, 5(1),* 98-113.

Meier, G. E., Grabitz, G., Jungowski, W. M., Witczak, K. J. & Anderson, J. S. (1980) Oscillations of the supersonic flow downstream of an abrupt increase in duct cross section. *AIAA Journal, 18(4),* 394-395.

Neumann, E. P. & Lustwerk, F. (1949). Supersonic diffusers for wind tunnels. *J. appl. Mech., 16*(2), 195-211.

Savin, A. V. & Sokolov, E. I. (1998) Influence of rarefaction on oscillations in an underexpanded jet impinging upon a flat plate. *Proceedings of Proc. 21st Intern. Symp. RGD*, 623-630.

Semiletenko, V. G., Sobkolov & B. N., Uskov, V. N. (1972) Sheme of shock-wave processes in an unstable interaction between jet and an obstacle. *Journal of USSR Academy of Science. Technical sciences, 13(3),* 39-41.

Sizov, A. M. (1987) *Gas dynamics and heat transfer of gas jets in metallurgical processes.* Moscow: Publishing house "Mettalurgy". 256p.

Wick, R. S. (1953) Effect of boundary layer on sonic flow through an abrupt cross-sectional area change. *J. aero Scl., 20(10*), 675-682.

Zapryagaev, V. I., Uskov, V. N. & Gaponov, S. A. (2000) *Jet and Unsteady Flows in Gas Dynamics*. Novosibirsk: Siberian Branch of the Russian Academy of Sciences Press. 245p.