History of base pressure experimental research

Nikolay Vasilevich Prodan

Saint-Petersburg National Research University of Information Technologies, Mechanics and Optics, Kronverksky pr., 49, Saint-Petersburg, 197101, Russia

Abstract. In a series of three articles a review on the studies of separated flows in the vicinity of the aircraft's bottom parts , as well as of the nozzle devices with a break in generating line. These researches have been carried out since the early 50s of the last century. Definitions to the bottom pressure and bottom areas of various types are given. The problem statement of the study of separated flow in a channel with a sudden stream expansion is described. The history of the experimental research on the dependence of the bottom flow in the channel on the design parameters and conditions of the environment is discussed. Paid the attention to publications on the definition of flow's physical pattern in the channels and ejectors. The links to all important works in this domain are provided. The review will be useful for professionals, who work on the development of new high-speed transportation systems.

[Prodan N.V. **History of base pressure experimental research.** *Life Sci J* 2014;11(7s):238-241] (ISSN:1097-8135). http://www.lifesciencesite.com. 48

Keywords: bottom pressure, bottom resistance, separated flow, flow with sudden expansion.

Introduction

One of the most pressing problems that arise in aircraft and space-rocket transportation systems the design is the task of reducing the bottom resistance. For at least the last sixty years, a research of the flow in a cylindrical channel with the sudden flow expansion was used for simulation of the flows near the aircraft's bottom and in the propulsion system's nozzles.

Among the many problems in gas dynamics, which are related to the interaction of supersonic jets with obstacles, the flow of supersonic jets in channels with a sudden expansion is of a special kind, related to the separated, and the problem itself, in a sense, is classic . Such flows are realized in various technical devices of space-rocket laser systems: in the launch tubes of the starting plants, nozzles with a break in generating line, diffusers of tall stands and technological processing plants (lances and blowing devices of metallurgic furnaces, gas fixtures and pipes of the chemical industry).

Problem of studying the supersonic separation flow with sudden flow expansion in a cylindrical canal

A phenomenon of the turbulent separation, like any natural phenomenon, appears more complex in its properties, forms and manifestation as it becomes more deeply studied. However, from a practical point of view, the study of turbulent separation made undeniable progress, whereby a developed separation and its main properties can be predicted and properly considered in the design of technical devices. The variety of real turbulent separated flows, their complex physical nature and lack of general theories lead to the need of combining the physical experiment, calculated approximations and analytical studies to a greater extent than in other areas of gas dynamics. The problem of supersonic jets' propagation in channels with a sudden expansion (Fig. 1) is traditional for applied gas dynamics. Intensification of researches in this direction is due to the practice requirements to create new transport vehicles, as well such designed for supersonic flights.

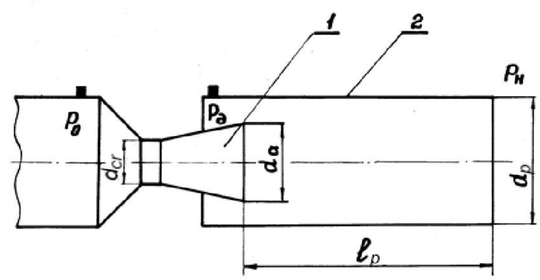

Fig . 1. The geometry of the channel with a sudden expansion

Figure 1 shows the parameters that uniquely characterize the geometry of the nozzle 1 and of the channel 2. Such are: d_{cr} - radius of the nozzle's critical section, da - diameter of the nozzle's exit section, θ_a - angle of a nozzle's half-opening at its section, d_p - canal diameter, l_p - canal length.

Separated flows in canals

There are many papers, dedicated to investigation of internal separated flows and the bottom pressure, related to it. According to the book "Fundamentals of gas dynamics" [1] the first researcher of the flow with sudden expansion is considered to be Nusselt, who were performing the experimented with transonic stream, flowing from a tapering conical nozzles. He compared the obtained results with calculations based on one-dimensional theory.

The needs of the rapidly developing aviation technology, and later rocket technology stimulated research of internal separated flows. These studies were carried out in many countries and the publication about the research of the processes occurring in the channels during the flowing of a supersonic jet from the nozzles and features of bottom pressure changes appeared about the same time. Here the works of Newman and Lustwerk - 1949 [2], [3], Chapman - 1950 [4], Lukashevich - 1953 [5], Fabry Sistrunk - 1958 [6], Korst - 1956 [7], Egink - 1955 [8], Karashima - 1961 [9] can be specified. One of the most important works on the stating of bottom pressure problem is the work of Chow [10]. In our country, the publication in the open press came later, but it does not mean that researches in this direction have not been conducted.

Single-dimensional approach was used as well in the analysis of gas flow in the pipe by I.P.Ginzburg [11] to determine the loss of bottom pressure after the expansion during a supersonic gas flow through a narrow section of the pipe. Referring to experimental data of Wick [12] about the bottom pressure, the ratio of the total pressure loss was determined. The flow regime, at which in a wide part of the pipe the shock wave (in different words – such small area, while passing which the velocity instantly changes from supersonic to subsonic and the pressure increases drastically) can occur is also discussed in the book [11]. To determine the pressure of adiabatically decelerated gas behind the shock wave the Rayleigh formula is used.

The research of ejector systems without secondary flow with cylindrical mixing chamber using a one-dimensional approach is made in the work [1]. Using the energy conservation equation and taking into account the force of friction on the surface of the mixing chamber, the ranges of equations' solutions existence for the calculation of relative bottom pressure.

In their studies, Fabry and Sistruck [6], using conical and expanding nozzle with Ma = 1.836, revealed the existence of ejector's three operating regimes: mixed, transient, and supersonic, during which a gas flow with different velocities occurs in a canal; revealed the existence of the minimum limit values for bottom pressure for the conical and profiled nozzle and a its subsequent increase as the total pressure at the nozzle inlet grows. To physically illustrate the flow regimes during operation [6] a series of shlieren-photografies of the wave structures, obtained on a flat installation with transparent walls are provided. These photos correspond to different phases of establishing a supersonic gas flow in the canal, starting the separated flow in a flat nozzle to the separation of bottom region from from the external atmosphere and the formation of X-shaped shocks . Attention is drawn to the fact that the moment of locking bottom region is corresponded with such transverse dimension of the jet, which exceeds the cross-sectional area of the canal. The canal walls prevent the expansion of the jet.

Research of the bottom resistance of the shells

Works in the field of missile ballistics have long been associated with the problem of sudden expansion of external compressible flow behind the bottom cut of the shells and the bottom pressure. A significant portion of the total resistance is the resistance caused by bottom rarefaction. It is now known that at high flight speeds bottom pressure is lower that atmospheric pressure. Methods, related to ballistic tests, only allowed to investigate the bottom pressure dependence on flight's Mach number. Chapman's series of experiments showed that the boundary layer has a certain effect on the bottom pressure. Chapman also proposed an experimental criterion of the dependence of bottom pressure on the boundary layer's modified thickness.

Internal and external bottom area.

With all the analogies between external and internal separated flows there are differences between them as well. These differences lie in the fact that the flow lines of the boundary layer in the canal almost constantly intersect with the characteristics of the rarefaction wave, which does not occur in the external flow. The intersection point of the first rarefaction wave characteristic with the boundary layer gives the maximum possible rarefaction at a given Mach number, and hence a lower base pressure for the jet, intersected by Mach lines.

In addition, the shift stress and boundary layer separation in internal and external flows are nonequivalent.

The difference lies also in the fact that the expanding external flow is drained to the axial zone (Fig. 2), forming, in the absence of bottom blowing, the return flow to the bottom of the missile and a closed bottom region with the recirculation flow. In the presence of the blowing, for example, through a nozzle, the bottom region with recirculating flow has toroidal shape (Fig. 3). When internal flows in a canal expand beyond the nozzle section, the flow spreads over the wall of the canal and forms a closed bottom region, a reverse flow in which is directed along the canal wall (Fig. 4). If the total pressure in front of the nozzle is insufficient, the annular gap is formed between the boundary of the jet and the canal's wall, in which rushes the gas from the environment (Fig. 5).

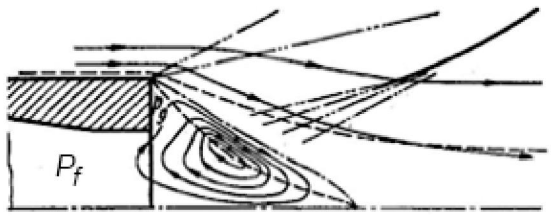

Fig. 2. External separated flow in the absence of blowing into the bottom region. P_f * - pressure in the pre-chamber

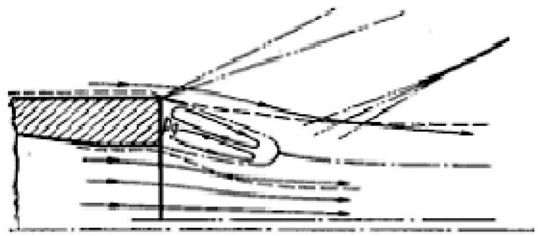

Fig. 3. External separated flow and toroidal bottom region in the presence of blowing

Fig. 4. Internal separation flow in the canal

The bottom area ∂ is closed. q_p - air masses, ejected by the jet, which flows from the nozzle section a, from the bottom region ∂, q_v - air masses, returning into the bottom area ∂ from the region R, where the jet is attached to the canal wall.

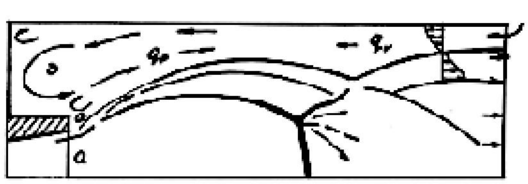

Fig. 5. Internal separation flow in the channel. The bottom area is open. Legend - as in Figure 4

Researches, aimed at determining the flow pattern in the canal

Experimental researches of the separated supersonic flows, conducted later contributed to a deep and comprehensive study of this phenomenon. Emphasis has been still made on obtaining a reliable pattern of the supersonic flow in the canal and quantitative dependences on the bottom pressure. These studies include works carried out by Anderson and Williams [13], Martin and Baker [14] and Jungovski [15], [16]. All these works contain the study of sonic research and supersonic jets' flow in canals with a sudden expansion and the visualization of wave structure, using flat installations with transparent walls. In papers there are either photos of wave structure, obtained by the shadow method, or interferograms, corresponding to different phases of the flow's formation in the channel.

In the work [13] the schematics of the flat supersonic stream near the nozzle section with the emission of recirculating flow in the bottom region are provided. The features of the interaction between the jet boundary and the canal wall and the formation of reflected shock, which passes then through a Prandtl - Mayer zone of rarefaction waves are shown. For axisymmetric canal of limited length, the research of the changes in bottom pressure P_d, depending on the total pressure P_0 [14] is performed. Studies have shown the existence of a typical dependences of bottom pressure change for sonic nozzle and hysteresis phenomena, accompanying the restructuration of the wave structure on increasing and decreasing total pressure P0.

Experimentally researching the startup process of the diffuser with the Eiffel chamber on the installation, which has a nozzle with M_a = 2.72 and diffusers of three different diameters, it was confirmed that the changes of bottom pressure and distribution of static pressure over the canal's wall have general patterns [17]. Researches Bespalov A.M., Mikhalchenko A.G. and V.G. Serebriakov continued the work on the revealing the features of the gas flow in the canal for different values of P_0, on flow regimes with open or closed bottom area.

The regime with open bottom area is distinguished by significant positive gradient of static pressure, which causes the inflow of excessive gas masses into the bottom region. The regime with closed bottom area is distinguished by minimalizing of the bottom pressure and periodic local increases of the static pressure at the canal wall beyond the point of jet's attachment.

In the work [17] it is stated that the interaction of boundary-layer with a shock wave in the connection area cannot be neglected.

These parameters include the Mach number at the nozzle exit section and the thickness of the flow's boundary layer before the separation. In this paper of O.I. Gubanova [18] it is shown that the pressure in the bottom region depends on the thickness of the boundary layer, and studies Glotov G.F. and Moroz E.K. [19] show that increasing the relative thickness of the boundary layer almost by a factor of 2 does not result in considerable change of the bottom pressure value. Works, presented in this review are part of the extensive studies of separated flows, reflected in the book "Fundamentals of gas dynamics" [1], monographs of P. Zheng [20], [21], Svec A.M. and Svec T.N. [22], L.V. Gogish Stepanova and G.Y. [23] , Sizov A.M. [2], [24], [25], A.A. Shishkov [26], [27].

Conclusion

Experimental studies of separated flows with a sudden expansion on stationary regimes laid the foundation for the creation of methodologies for calculating aircraft's bottom pressure and bottom resistance, as well as served as a basis for further investigation of non-stationary regimes and transient processes.

Extensive researches of the bottom pressure are included studies that reveal the influence of different gas-dynamic and structural parameters of installations and stands.

Findings

Researches, carried out in the latest fifty years allowed to identify and classify the main regimes of separation flows with sudden expansion. The variety of these regimes, non-stationary, oscillatory phenomena, a large range of pressure changes make the flows with sudden expansion attractive for usage in technological processes.

Acknowledgements

This article was prepared as part of the "1000 laboratories" program with the support of Saint-Petersburg National Research University of Information Technologies, Mechanics and Optics (University ITMO).

Corresponding Author:
Dr. Prodan Nikolay Vasilevich
Saint-Petersburg National Research University of Information Technologies, Mechanics and Optics
Kronverksky pr., 49, Saint-Petersburg , 197101, Russia

References

1. Krokko L., 1963. One-dimensional consideration of steady flows gas dynamics: Fundamentals of Gas Dynamics [ed. Emons G.M.]: 269–274.
2. Sisov A.M., 1987. Gas dynamics and heat transfer of the gas jets in metallurgical processes. M.: Metallurgy, pp: 256.
3. Neumann E.P. and F. Lustwerk, 1949. Supersonic diffusers for wind tunnels. J. appl. Mech., 16(2): 195.
4. Chapman D.R., 1950. An analysis of base pressure at supersonic velocities and comparasion with experiment. NASA. – Tech. Note 2137.
5. Lukasiewicz J., 1953. Diffusers for supersonic wind tunnels. J. aero Sci., 20(9): 585.
6. Fabri J. and R. Siestrunck, 1958. Supersonic air ejectors. Advances in applied mechanics, 5.
7. Korst H.H., 1956. A theory for base pressure in transonic and supersonic flow. Trans ASME, Journal of applied Mechanics, 23(4): 593-600.
8. Egink H., 1955. Improving of pressure recovery in supersonic wind tunnels (№5). M.: Mechanics.
9. Karashima K., 1961. Base pressure on two-dimensional blunt-trailing-edge wings at supersonic velocity. University of Tokyo, Aero, Research Institute Report 368.
10. 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.
11. Ginsburg I.P., 1958. Applied hydroaerodynamics. L.: LSU.
12. Wick R.S., 1953. Effect of boundary layer on sonic flow through an abrupt cross-sectional area change. J. aero Sci., 20(10): 675-682.
13. Anderson J.S. and T.J. Willams, 1968. Base pressure and noise produced by the abrupt expansion of air in a cylindrical duct. J. Mech. Engng Sci., 10(3): 262-268.
14. Martin B.W. and P.J. Baker, 1963. Experiments on a supersonic parallel diffuser. J. Mech. Engng Sci., 5: 98-113.
15. Jungowski W.M., 1969. On the flow in a sudden enlargement of a duct. Fluid Dynamics Transactions, 4: 231-241.
16. Jungowski W.M., 1967. On the pressure oscillating in a sudden enlargement of a duct section. Fluid Dynamics Transaction, 1: 735-741.
17. Bespalov A.M., A.G. Mikhalchenko and V.G. Serebryakov, 1973. Study of startup process of supersonic wind tunnel diffuser with the Eiffel camera. Central Aerohydrodynamic Institute Scientific reviews, 4(1): 125–132.
18. Gubanova O.I., 1974. Using the weight average values method for bottom pressure and enthalpy calculation: Coll. of res. papers. Inkjet and separated flows [ed.Kirsanova B.S.], 3(1): 68–83.
19. Glotov G.F. and E.K. Moroz, 1970. Study of axisymmetric flows with a sudden expansion of the audio stream. Works of Central Aerohydrodynamic Institute, 1281: 31–39.
20. Zheng P., 1972. Separated flows. M.: Mir. vol. 1-3.
21. Zheng P., 1979. Management of flow separation. M.: Mir, pp: 552.
22. Shvets A.I. and I.T. Shvets, 1976. Gas dynamics of the near wake. Kiev: Naukova Dumka, pp: 384.
23. Stepanov G.Yu. and L.V. Gogish, 1973. Quasi-one-dimensional gasdynamics of jet engine nozzles. M.: Mashinostroenie, pp: 167.
24. Sisov A.M., 1991. Dispersing of melts with supersonic gas jets. M.:Metallurgy, pp: 184.
25. Yavoisky A.V., V.L. Yavoisky and A.M. Sisov, 1985. Application of pulsing blast in steel production. M.: Metallurgy, pp. 176.
26. Shishkov A.A., 1968. Gasdynamics of powder rocket engines. M.:Mashinostroenie, pp: 148.
27. Shishkov A.A. and B.M. Silin, 1985. High-altitude rocket engine tests. M.: Mashinostroenie, pp: 208.

5/1/2014