Development of the bottom pressure calculation methods

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Abstract. Work is dedicated to semi-empirical and integral methods of calculating the pressure in the aircraft's bottom region at stationary regimes. Historical information on improving the methods of calculation and mathematical models is given. The problem statement of calculating the bottom pressure is discussed. A complete set of gas-dynamics variables is formulated, which, at given installation's geometry, completely determine the flow pattern in the bottom region. Different variants of bottom pressure calculation methods based on the concept of the dividing stream-line are reviewed. The data on the work to develop more universal methods of integral calculation are provided.

[Bulat P.V., Bulat M.P. **Development of the bottom pressure calculation methods.** *Life Sci J* 2014;11(7s):203-208] (ISSN:1097-8135). http://www.lifesciencesite.com. 40

Keywords: bottom pressure, the dividing stream-line, integral methods.

Introduction

Bottom resistance of the aircraft at supersonic speeds can be up to 40 % of the total resistance. It is required to be able to calculate the base pressure to find the ways to reduce the bottom resistance. On the contrary, in other technical devices, such as ejectors, altitude conditions simulation stands, the task is to decrease the bottom pressure. Numerical calculation methods currently allow to relatively successfully calculate the flow in the vicinity of bottom areas in conditions where the influence of non-stationarity and large-scale turbulence can be neglected. Important is the ability to set right boundary and initial conditions. Often it is enough to know the average integral values of pressure in the bottom area, and the flow pattern does not matter. For such tasks the diagnostic calculation methods still remain relevant.

Statement of the problem of calculating the bottom pressure

In separated flows with sudden expansion (FWE), a bottom area in which, due to ejecting influence of the jet (or external supersonic flow), the characteristic pressure is lower than in the environment or in the main (concurrent) stream. Vortex flow in this region is significantly subsonic. The main geometric parameters f_G, on which the pattern of the flow with a sudden expansion depends are (see Figure 1): the radiuses of the critical (R^*), internal (R_a) and external (R_c) output nozzle's section, (θ_a) angle of half-opening of the nozzle at its cut and canal radius (R_k).

It is convenient to use dimensionless quantities: L_K - dimensionless length of the canal (often instead of index "k", the index "tr" is used, i.e. the symbol L_k is equivalent to L_{tr}), F_{fr}/F^* - area of the canal, divided by the area of the nozzle critical section, M_a - geometric Mach number of the nozzle. Nozzle position in the canal is determined by the length of the nozzle's carry-over into the canal (L_a), which affects the volume of bottom region, and by the canal length L_k.

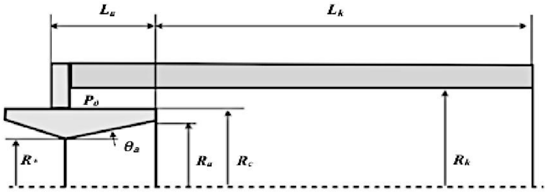

Fig. 1. The geometry of a channel with a sudden expansion

R^* - the radius of the critical nozzle section, R_a - radius of the internal output section of the nozzle, R_c - radius of the external output section of the nozzle, θ_a - angle of nozzle's half-opening at its cut, R_k - canal radius , L_K - canal length, L_a - length of the nozzle's carry-over into the canal.

With the given nozzle and canal geometry, the flow is completely determined by the sets of gas-dynamics variables f_0, which describe the parameters of deceleration of working gas flowing out of the nozzle, and f_n – parameters of the gas, filling the canal prior to the ejection of the jet. The sets $f_{0,h}$ consists of the thermodynamic and thermophysical variables f, which define the state of the working and surrounding gas: p - pressure, T - temperature, $\gamma = C_p/C_v$ - the adiabatic index, and others that affect the bottom pressure (P_b) in the vicinity of the Laval's nozzle exit. The ratio between the static pressures of the working gas at the inner edge of the nozzle and the bottom area ($na = P_a/P_d$) defines a local un-calculability of jet outflow from nozzle unlike the value $n = P_a/P_i$, which is usually used as the main parameter characterizing the outflow of a jet from the Laval nozzle into the surrounding space. The task is to find the value of average pressure in the bottom area at given conditions f_n of the environment.

Formation methods for calculating bottom pressure

Some of the research results on the conditions for realization of the supersonic flow regime in the canals can be found in the works of Gusev V.K. [1] Getert [2], in Articles of Davidson V.E. Chuhalo N.A [3], Oyknine and Fortanier [4], Benedict [5], Kan [6], but their usage for practical calculations in a wide range of parameters is difficult.

A.A. Shishkov in his work [7] proposes to determine the pressure, at which the supersonic flow appears in the exhaust diffuser of high-altitude stand using the one-dimensional theory on the assumption that the velocity therein is changed from subsonic to supersonic and the total pressure recovery coefficient is the same as in the forward shock. To improve the alignment between the calculated and experimental data in the work [7] the match coefficient, which takes into account the deviation of the actual process from the one-dimensional calculation model of an ideal gas flow is introduced. At high ratio between the diffusor's diameter to the diameter of the outgoing nozzle section the calculations using one-dimensional theory does not produce satisfactory results.

Virtually all recearches of jet flow in canals with a sudden expansion, while conducting visualized studies of wave structure, were performing measurements of the pressure distribution along the generator line of the canal. Such measurements are present, as already noted, in the first papers for Sistrunk and Fabry [8], and then this trend has continued in the work of Anderson and Williams [9] V. Davidson and Neshcheret P.A. [10] Batson and Bertin [11], [12] G.F. Glotov and Z.K. Moroz [13] A. Bespalov , A.G. Mikhalchenko and V.G. Serebriakov [14]. In all these works the periodicity of the static pressure distribution increase at the wall of the canal, corresponding to the frequency of repetition zones, which reflect the shocks of X - shaped structure off the canal wall on a stable regime of supersonic gas flow through the canal.

In the work [10], according to the results of experimental studies, an empirical method for determining the minimum value of the pressure at the wall, as well as the maximum peak values in areas falling shocks is proposed.

In the work [14], in addition to the bottom pressure and the pressure distribution along the canal wall the total pressure along the axis of the canal was experimentally determined, using the receiver of the total pressure. These research with the measurements of the fields of parameter distribution over the canal's sections on a stable supersonic regime were continued in the works of Davidson V.E. and Neshcheret P.A. [15] for external atmospheric pressure on a section of the channel, and for the reduced - in the works of E.A. Leites, N. Nesterov, V.A. Chomutov [16], Anderson and Meyer [17].

However, one of the major problems in the study of separated turbulent flow still is to determine the pressure in the most stagnant zone - bottom pressure.

In the work [18] the methods of calculating the bottom pressure, built by analogy with the outflow of inviscid free unexpanded jet in flooded space, under the assumption that the boundary line of the jet flow comes in contact with the canal wall. This assumption is similar to the assumption that the presence of the canal walls does not affect the nature of the flow stream prior to its contact with the wall, and the change only affects its degree of expansion. The analysis of the calculation data, given in the work [18], shows that the difference between the results of the experiments is about 15 - 20% and in some cases even more. I.e. such scheme describes the flow very approximately.

Improvement of methods for separation flow line (SFL)

Great influence on the development of methods for calculating the bottom pressure at the external and internal separated flows sad the work of Crocco-Lis [19], which consisted the theory for mixing during the interaction of dissipative and nearly isentropic flow, and the works [20], [21], which contained the basic provisions of the Chapman - Corsten model on the calculation of bottom pressure. In the basis of this model (Fig. 2) lies the assumption that, when the flow leaks on the wall behind the ledge there is a flow line, which separates the part of the gas flowing from the viscous layer into the stagnant zone from the main flow.

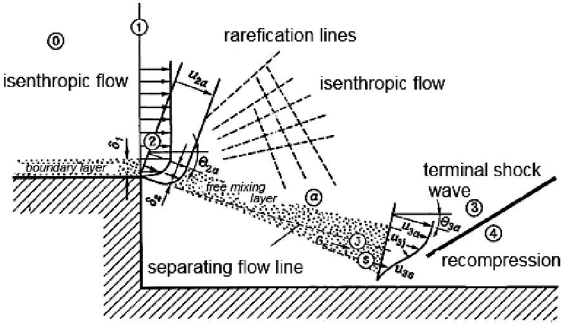

Fig. 2. Model of the flow in Corsten's SFL method

This flow line, called the separating flow line (SFL), is characterized in the model Chapman - Corsten by the property of equality of the total pressure on the this line at the point of attachment to the wall to the maximum static pressure beyond the area of attachment. This assumption allowed Corsten [21] to determine the base pressure behind a flat ledge.

SFL method was used by Bondarev E.N. [22], Eddie and Chau [23], [24] in the calculation of separation flow to assess the bottom pressure behind the ledge in the flow of supersonic stream. Most studies have shown that in the flows with sudden expansion the boundary flow line of the inviscid jet approaches the wall of the canal is not by a tangent, but at some angle [14], [2], [25], [7], [26], [27]. Such an assumption is made as to the flow model proposed by Corsten [28], in which, as was already noted, the equality of the total pressure on the separation flow line at the point of attachment to the wall to the maximum static pressure behind the area of attachment was taken as the criterion of attachment.

As shown by the detailed physics research, in fact, this criterion is not satisfied. The studies of Wick [29] R.K. Tagirov [18], [29], [30], Nash [31] Career and Sirje [26], [32], [33-35], Kessler [36] Yurchenko K.E. [37] Tanner [38-40], and other authors detected the necessity for the introduction of corrections, which would improve the matching between the calculated and experimental data the scheme of Chapman - Corsten.

In the work [31] the parameter N = (R_{0a} - P_d)/(P_i - P_d), representing the ratio between the pressure difference in the point of attachment and in the stagnation zone R_{0a} and the difference of static pressure in the oncoming flow P_i and in stagnation zone R_d. On the basis of experimental data obtained for flat flow with turbulent boundary layer the values of the parameter N were calculated, depending on the M number of the oncoming flow and show that at supersonic speeds the value N = 0.35, whereas the Corsten criterion corresponds to the value of the parameter N, equal to one.

In the works [21], [39], [33-35], performed in ONERA, as adjusted criterion of attachment, the meeting angle of the boundary of inviscid jet with the canal wall was introduced, built by the method of characteristics according to the pressure ratio P_g/P_0* (where P_0* is the pressure at the wall in the point of leak-in), which was determined experimentally. Comparison of dependence, obtained in this way is θ = θ (M_{gr}), where θ – meeting angle of the jet boundary with the wall, and M_{gr} - Mach number at the boundary of the jet. It is shown that these values are significantly different from the values obtained in works [21], [19].

In contrast to the attachment conditions of Chapman – Corsten in the work [40] a simplified model of attachment is considered, which use a more consistent assumption that the influence of viscosity at the outer boundary of the jet near the wall can be neglected. Conditions of attachment and separation of the boundary layer, formulated on the basis of this assumption, provide sufficiently accurate results with a minimum usage of common empirical constants.

The authors of the work [41], using the method of separation flow line to calculate the bottom pressure, suggested that at large values of ratio between the canal cross-sectional area to the area of the nozzle section, the different regimes are possible, in which the interaction occurs:

first – interaction in the area of thinning wave;

second – in the inner hypersonic zone, in which the pattern of leak-in is similar to flow from the source.

Comparison of the physical experiments' results and calculated data - showed that in different ranges, which define the parameters, the experimental data is close to one or another case of interaction. Introduction of an additional dependence of attachment parameter allows to decrease the difference between the values of the results for the real flow conditions, located between two extreme modes of interaction.

Theoretical basis of the methods for calculating the bottom pressure

In the work [42], V.M. Blagosklokov and V.A. Chomutov, using the calculation method, revealed the influence of gas isentropic value on the longitudinal coordinate and maximum values of the first pressure peak along the generating line of the canal. The determining of this dependence was performed using shock-capturing method with the usage of experimental data regarding the bottom pressure.

Theoretical aspects of bottom pressure dependences on the automodel and non- automodel regimes were discussed in the works of Zelenkova O.S. [43-44, 25]. The non- automodel regime stands for such regime, when the difference between the pressure at the nozzle section and the ambient pressure at the canal cut was not high enough. In these cases, the solution by the method of separation flow line (SFL) is impossible without significant modification (taking in account the longitudial pressure gradient). Usage of the integral methods allowed to obtain a number of important characteristics: the dependence of bottom pressure on the total pressure in the jet, the pressure distribution along the canal wall, as well as to determine the moment of transition from non-automodel to automodel regimes. The developed method allowed to carry out the numerical calculations of the flows in the mixing zone, reverse flows into the bottom area, and to consider the effect of blowing into this area.

Calculation of the attached mass value was discussed in works [45], [44] performed by Zelenkov O.S. together with A.V. Yurkov.

Features of sonic and supersonic jets flow in cylindrical and conical expanding and converging nozzles at small relative areas of the canals, applied to the ejector nozzles were discussed in the works of Glotov G.F. and Z.K. Moroz [13]. In these researches, the relative canal length was measured by the height of the ledge and all the data is applicable to short canals, in most cases, shorter than the optimum pipe length lopt. The length of the canal is called optimal, if the minimum value of bottom pressure can be achieved. Studies were designed to verify the pattern of the flow (Figure 2) to create a more universal method of calculating the attachment criterion than the criteria of Corsten [46] and Nash [47]. Studies have shown that the attachment of the flow to the canal wall occurs in the initial part of the jet up to the maximum cross-section of the corresponding free jet, and the attachment of separating flow line is characterized by constant ratio between total pressure at the attachment point and the pressure in the stagnant zone. The developed scheme of the flow in the zone of attachment is characterized also by containing the essential elements such as: the location of the flow separation line in the subsonic part of the viscous layer, the turning of the separation line by the angle of 90° to the wall, the presence of a local vortex near the wall in a stagnant zone and turning of the main flow’s boundary part at the wall in the system of shocks behind the separation line.

Integral methods for calculating the bottom pressure

In their works, L.V. Gogish and G.Y. Stepanov were using the integral methods with various forms of integral equations and relations (which were obtained from the equations of boundary layer [48-54]) for the calculation of turbulent separation flows. These papers contain the results of calculating the bottom pressure beyond the body in unlimited stream. Dependences of the relative bottom pressure beyond the ledge on the relative total pressure for different canal sidewall lengths, obtained in [48] are similar to the wide-known experimental dependences for the ejection nozzles. They are characterized by the existence of flow regimes with both open and closed bottom area and by the hysteresis of typical parameters in the area of transition between them. In contrast to the results, in which the model of Chapman – Corsten was used, it is found that is available relative total pressure, at which the closure of the bottom region occurs and the value of bottom pressure significantly depend on the length of the canal.

Conclusion

Semi-empirical and integral methods for calculating the bottom pressure, developed over the past 60 years, allow to qualitatively and correctly describe the dependence of bottom pressure on basic geometric parameters and conditions in the external environment. However, they are not able to predict the change of the flow regimes and the occurrence of non-stationary processes.

Findings

The duration of the studies in the field of developing the semi-empirical methods for calculating the bottom pressure indicates the complexity, and the urgency of this task. The rapid development of numerical methods somewhat reduced the significance of empirical models, because their programming is still very complex. However, the theoretical justification of the modern turbulence models applicability for the calculations of unsteady flows requires some effort to find their limits. This is what the semi-empirical models are currently used for.

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).

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5/1/2014