ISSN 1063-7850, Technical Physics Letters, 2020, Vol. 46, No. 6, pp. 579–582. © Pleiades Publishing, Ltd., 2020.
Russian Text © The Author(s), 2020, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2020, Vol. 46, No. 12, pp. 10–13.

Duality of the Vortex Structure Arising in a Supersonic Viscous Gas Flow Past a Plate and a Blunt-Fin Body Junction

E. V. Kolesnik[a]*, A. A. Smirnovsky[a,b], and E. M. Smirnov[a]

[a] *Peter the Great St. Petersburg Polytechnic University, St. Petersburg, 195251 Russia*

[b] *Ioffe Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia*

**e-mail: kolesnik_ev@mail.ru*

Received March 5, 2020; revised March 14, 2020; accepted March 18, 2020

Abstract—The results of a numerical solution of the problem of supersonic flow past an elongate blunt-fin body mounted on a plate with developing laminar boundary layer are presented. The calculations cover flow cases with the freestream Mach number equal to 6.7 and two different Reynolds numbers: Re = 1.25×10^4 and 1.56×10^4. The structure of the horseshoe vortices arising in the body leading-edge region is analyzed. It has been revealed that, for both Re values, there are two stable solutions that correspond to different metastable states of the flow. The solutions differ in the number of vortices forming in the separation region and its length. In the smaller Reynolds number case, both solutions are steady-state, whereas in case of a larger Re value one of them remains steady-state, and the other one becomes quasi-periodic.

Keywords: numerical simulation, high-speed flows, viscous-inviscid interaction, horseshoe-shaped vortex structures, duality of solution.

DOI: 10.1134/S1063785020060206

In a flow past a blunt-fin body mounted on a plate, a complex vortex structure arises, characterized by a different configuration of horseshoe-shaped vortices. A large number of studies are devoted to investigation of the topology of the vortex structure depending on the flow parameters for the case of a subsonic flow [1, 2]. In the case of a supersonic flow around a body, the resulting shock waves lead to complex effects of viscous–inviscid interaction, which significantly affects the vortex structure. Such problems, which are important both theoretically and for practical applications, for example, in the aerospace industry, have also been studied by many researchers (see, for example, [3–7] and references therein). The model problem of supersonic viscous gas flow around a blunt body in the form of a stream-oriented thick plate with a rounded leading edge is most often considered. In particular, in the calculation and experimental work [4], for this model configuration, the structure of the laminar flow in front of the streamlined body was studied for three values of the Reynolds number constructed by diameter: $\mathrm{Re}_D = 1.25 \times 10^4$, 2.50×10^4, 3.75×10^4. For all Re_D values, the authors of [4] interpreted the obtained numerical solutions as stationary and unique. Later, in a computational study [5], it was shown that the solution even at $\mathrm{Re}_D = 2.50 \times 10^4$ is unsteady.

The purpose of this work is to clarify the possibility of the duality and/or unsteadiness of the numerical solution of the viscous–inviscid interaction problem for the same model configuration for values of the Re_D number in the range from 1.25×10^4 to 2.50×10^4. To a certain extent, this work is a continuation of our studies [8], in which, at lower Reynolds numbers, the influence of the Mach number, plate length, and temperature factor on the flow structure and heat transfer was studied.

The calculations were carried out in two problem formulations: for half of the considered configuration (the computational domain is shown in Fig. 1) and in the complete computational domain without the condition of symmetry in the median plane *XZ*. According to the used model of a viscous perfect gas, the flow is determined by the following set of dimensionless parameters: free-stream Mach number M, Reynolds number Re_D constructed from blunt diameter D, Prandtl number Pr, temperature factor T_w/T_{in} (T_{in} is the free-stream temperature), and adiabatic exponent γ, as well as length of the plate L_{plate} to the junction. Numerical solutions to the problem were found for a set of parameters corresponding to the data of [4]: M = 6.7, $T_w/T_{\mathrm{in}} = 4.75$, Pr = 0.7, $\gamma = 1.4$, and L_{plate} = 145 mm. The calculations were performed at two Reynolds numbers: $\mathrm{Re}_D = 1.25 \times 10^4$ and 1.56×10^4

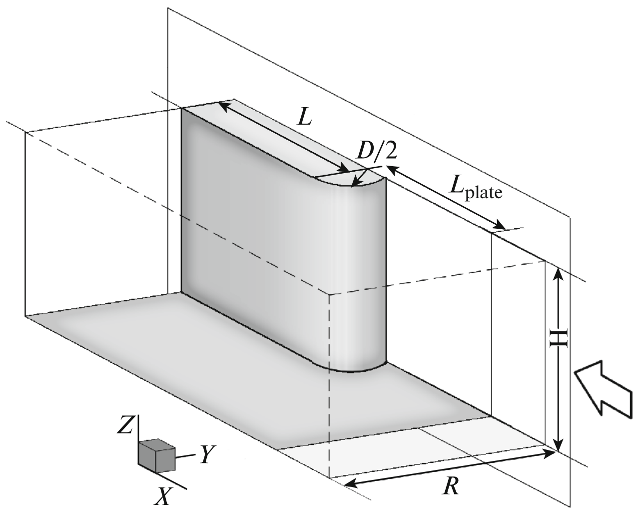

Fig. 1. Computational domain.

(varied due to a change in D from 2.5 to 3.125 mm). A uniform flow was set at the inlet boundary of the computational domain, and the no-slip condition was set on the body surface and plate. A constant temperature T_w was maintained for the surface of the body and plate.

For calculations (based on nonstationary formulation), the finite-volume "unstructured" SINF/Flag-S program code developed at the Institute of Applied Mathematics and Mechanics of Peter the Great St. Petersburg Polytechnic University was used. Details of the numerical scheme are given in [9].

In the case of the computational domain with the imposed symmetry condition, a quasi-structured grid consisting of 10 × 10^6 cells was first used. Then, in order to check the grid convergence, the calculations were also performed on a grid with 25 × 10^6 cells. Calculations for the "full" region were performed on a grid consisting of 20 × 10^6 cells. For calculations, the computing resources of the Peter the Great St. Petersburg Polytechnic University supercomputer center were used [10].

Previous studies (see, for example, [3–5]) showed that in a supersonic flow past a blunt-fin body mounted on a plate, the opposing pressure gradient leads to separation of the boundary layer. A recirculation flow with supersonic velocities arises inside the separation region (Mach numbers make up about a third of the incoming flow Mach number), as well as local compression waves, which leads to re-separation of the near-wall flow, and, as a result, an extended separation region is formed in front of the body containing a set of horseshoe-shaped vortex.

As a result of calculations starting from different initial conditions, it was found that, at Re_D = 1.25 × 10^4, there are two stable stationary solutions that correspond to two metastable flow states with different configurations of the vortex structure (Solution 1 and Solution 2 in Fig. 2a).

The first solution is characterized by a shorter separation region where the center of the main horseshoe-shaped vortex is shifted from the front edge of the body by a distance of about one caliber (D). In the second solution, the separation region is more extended, and the center of the main vortex is located almost twice as far from the streamlined body. In addition, the number of vortices in the second solution is one less (four vs. five).

The first solution with a given value of Re_D = 1.25 × 10^4 is obtained using uniform initial fields of

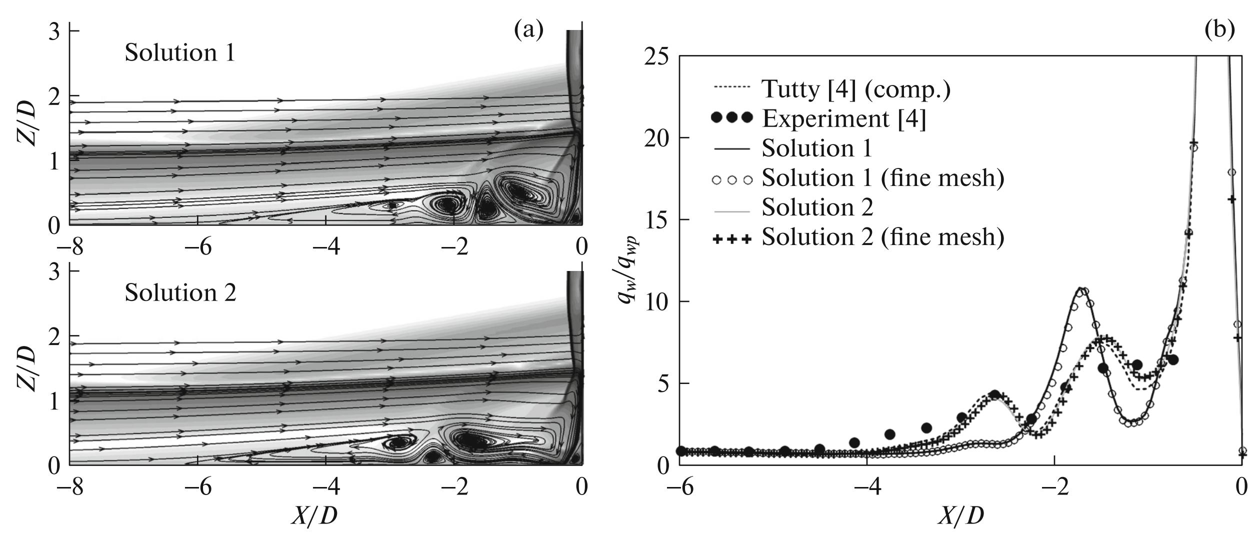

Fig. 2. The calculation results at Re_D = 1.25 × 10^4 for two solutions: (a) the field of the modulus of the density gradient and streamlines in the plane of symmetry; (b) the heat flux distribution along the line of symmetry.

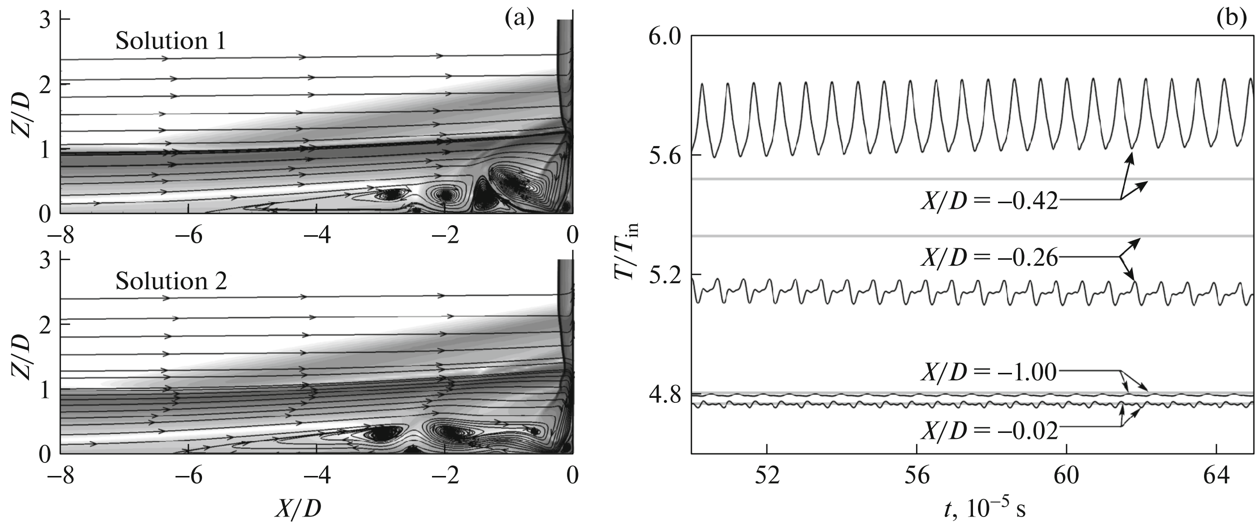

Fig. 3. The calculation results at $\mathrm{Re}_D = 1.56 \times 10^4$ for two solutions: (a) the field of the modulus of the density gradient and streamlines in the plane of symmetry (the nonstationary solution is averaged over time); (b) temporary changes in temperature at points near the surface of the plate.

the sought quantities, evaluated from the values of the flow parameters at the inlet of the computational domain. This regime is also established when specifying the initial conditions of the solution obtained with a significantly lower Reynolds number—in particular, for a fivefold decrease in the Reynolds number ($\mathrm{Re}_D = 0.25 \times 10^4$, starting from homogeneous fields). We also note that in the solution obtained at $\mathrm{Re}_D = 0.25 \times 10^4$ (not shown in the figures), the center of the main vortex is located at approximately the same distance from the body as in the first solution (Solution 1), shown in Fig. 2a. The solution of the second type is established when the instaneous fields of the nonstationary solution that develops from homogeneous fields with a noticeably higher Reynolds number are specified as initial conditions. Specifically, in this work, this "auxiliary" nonstationary solution was obtained for $\mathrm{Re}_D = 2.50 \times 10^4$, and the structure of the averaged flow field for this solution is similar to that shown in Fig. 2a for the second (stationary) solution in the case of $\mathrm{Re}_D = 1.25 \times 10^4$. The problem of finding possible bifurcation points or turning points of stationary solutions (stable and unstable) was not posed in this paper. The study of these issues, including clarification of the possibility of hysteresis, requires a very large amount of computations and will be the subject of a separate work.

Returning to the consideration of the features of the obtained solutions, it should be noted that the distribution of the relative heat flux along the line of symmetry on the plate (Fig. 2b), in addition to the global maximum (located outside the field of Fig. 2b), contains one more pronounced local maximum in the first solution and two local maxima of a lower level in the second solution. The latter is in good agreement with the numerical solution and experimental data from [4] (it should be noted here that in [4] there is no mention of the possibility of a dual solution).

Both solutions remain stable even in calculations in the full formulation (without imposing the symmetry condition). The refinement of the grid had practically no effect on the calculated flow fields (Fig. 2b). In particular, for the first solution, the maximum values of the Mach number of the recirculation flow (in the lower part of the main vortex) in the calculations on the initial and refined grids were 33.1 and 33.5% of free-stream Mach number M = 6.7, respectively.

When the Reynolds number is increased to a value of 1.56×10^4, one of the solutions (Solution 1) remains stationary, while the second (Solution 2) is unsteady with stable quasi-periodic flow oscillations, which are especially strong inside the separation region (Fig. 3a, for the second solution, the averaged time field). Earlier [8], we showed that an increase in the length of the separation region can be accompanied by a transition to an unsteady flow regime. Since, in the case considered here, the second solution corresponds to a separation region of greater length, it is the first to become unsteady with an increase in the Reynolds number.

In Fig. 3b, the value of relative temperature T/T_{in} at several monitoring points near the plate surface is presented (for comparison, the temperature values for the first stationary solution are also shown). Oscillations with the largest amplitude are observed near the streamlined body and in the region of the global maximum of the heat flux, and the oscillations are insignificant at $X/D < -0.8$. The configuration of the separation zone and its length and thickness practically do not change in time.

Three-dimensional numerical simulation of a supersonic flow of a viscous gas during its interaction with a blunt body mounted on a streamlined surface in the form of a flow-oriented thick plate with a rounded leading edge was carried out. Numerical solutions were obtained with a Mach number of 6.7 and two Reynolds numbers.

It was found that, for the Reynolds number $\mathrm{Re}_D = 1.25 \times 10^4$, there are two stable stationary solutions that correspond to two metastable states of the flow with different configurations of the vortex structure. The first solution is characterized by a less extended separation region and the location of the center of the main horseshoe-shaped vortex at a distance of about one caliber from the front edge of the body; in the second solution, the center of the main vortex is located significantly further from the streamlined body. The second solution is in good agreement with the experimental and calculated data of [4].

It was also shown that, with an increase in the Reynolds number to 1.56×10^4, one of the two solutions remains stationary, while the second is unsteady and is characterized by a stable quasi-periodic oscillations of the flow, which is especially strong inside the separation region.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

1. M. Y. Younis, H. Zhang, S. Mehmood, and J. Aslam, Sci. China Technol. Sci. **57**, 1342 (2014).
2. G. Launay, E. Mignot, N. Riviere, and R. Perkins, J. Fluid Mech. **830**, 257 (2017).
3. P. H. Schuricht and G. T. Roberts, AIAA J. **1579**, 1 (1998).
4. O. R. Tutty, G. T. Roberts, and P. H. Schuricht, J. Fluid Mech. **737**, 19 (2013).
5. Y. Q. Zhuang and X. Y. Lu, Proc. Eng. **126**, 134 (2015).
6. M. Mortazavi and D. D. Knight, in *Proceedings of the AIAA SciTech Forum—55th AIAA Aerospace Sciences Meeting, Grapevine, TZ, 2017*, p. 1.
7. O. A. Azarova, A. V. Erofeev, and T. A. Lapushkina, Tech. Phys. Lett. **43**, 405 (2017).
8. E. V. Kolesnik and E. M. Smirnov, Tech. Phys. **65**, 174 (2020).
9. E. V. Kolesnik, E. M. Smirnov, and A. A. Smirnovsky, Nauch.-Tekh. Vedom. SPbGPU, Fiz.-Mat. Nauki **12** (2), 7 (2019). doi .scc.spbstu.ru https://doi.org/10.18721/JPM.1220110
10. scc.spbstu.ru

Translated by N. Petrov