COMPUTATIONAL VISUALIZATION OF SUPERSONIC FLOW PAST HYPERSONIC FLYING VEHICLES MODELS

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ABSTRACT: Calculating results on the nature of supersonic flow past the models of various hypersonic flying vehicles are presented for a velocity range from 2 up to 6 Mach numbers. Five models with different control flaps have equal nominal outlines and the same base diameter. The separating model consists of two parts, the leader and block. In the initial assembled state the block is partially inserted into the leader having a smaller base diameter. The method of numerical solution of the complete Navier-Stokes equations averaged according to Reynolds and supplemented by a simple turbulence model has been selected for simulations. Results on the influence of flap area and shape on the nature of flow and aerodynamic characteristics were obtained for the models with control flaps in a wide range of angles of attack. The balancing angles of attack were determined. Results on the influence of leader and block relative positions on the nature of their aerodynamic interaction were obtained for the separating model. The distances between the leader and block, starting from which the change of the nature of their interaction took place and the block moving in a turbulent track began to come off the leader, were determined for various flow velocities.

INTRODUCTION. Flap control elements can be used for controlling, braking and stabilization of supersonic and hypersonic flying vehicles. They allow the parameters of controlling forces and moments to be varied at the expense of the rather substantial change of aerodynamic coefficients of the vehicles [1]. At supersonic flight velocities the complex picture of the flow past flying vehicles arises, especially in the areas of location of flaps, where detached flow conditions are realized. Obtaining the completely realistic data for detached flow conditions, especially under large angles of attack, is most practicable with the use of experimental methods at the present time. At the same time existing calculation methods already allow analyzing the picture of the flow past a flying vehicle in whole and obtaining quite acceptable results on the determination of its aerodynamic coefficients in a wide range of the change of flow conditions. Good agreement of such calculation results with the data of certain experimental measurements makes it possible to carry out the rated prediction for determining the values of these coefficients in practically any flow conditions.

The next type of hypersonic flying vehicles under study is the family of flying vehicles separating during the flight into two or more parts [2]. A variety of problems are related to the study of a separation process and to the development of suitable systems required for its realization. The problem of subsequent motion of the separated parts of such an apparatus is not less important too. One of the simplest cases here is the separation of an initially assembled system into the two coaxial parts moving in the same direction at the initial stage of flight. In this case the modern computation methods also allow analyzing the picture of a joint flow past both parts of a flying vehicle and obtaining quite acceptable results on the determination of aerodynamic coefficients of each of the parts.

The basis of an existing experimental-calculating complex for conducting the wide range of aeroballistic investigations of flying vehicle models [3] is the aeroballistic shooting gallery which allows recording the flight of models 1.6-14 cm in diameter and 1.6-41 cm in length at velocities of 130-3700 m/s with the use of photogrammetric and shadow optical methods [4]. A series of computer programs is used for experimental data processing [5]. The application of these programs makes it possible to extract a maximum amount of the data on aerodynamic characteristics of models of different flying vehicles from obtained experimental data. One of the programs of this series is the engineering hydrodynamic software program EFD.Lab, which is used for obtaining the preliminary values of static aerodynamic characteristics of models before their launching in the shooting gallery and the visual information on the character of a supersonic flow past models. As a result of conducted tests the great volume of experimental and calculated information on the aerodynamic characteristics and the visualisation of flow fields for the models of different supersonic and hypersonic flying vehicles have been obtained. Separate calculated results obtained for two types of tested models presented in this paper.

MODELS STUDIED AND CALCULATION METHOD. In this work the flow past two types of the models of hypersonic flying vehicles was studied. Five models used for studying the influence of the size and form of a control flap on the character of flow and aerodynamic characteristics [6, 7] were referred to the first type All these models had equal nominal contours and an identical base diameter D = 60 mm. Basic model 1 was without a control flap, model 2 and 3 had flat control flaps with areas of 0.04 S and 0.08S, where S is the area of the base of model 1. Model 4 had the flap of cylindrical form with the area of projection on a plane normal to the longitudinal axis of 0.10S. Model 5 had two diametrically opposite flat control flats with an area of 0.08S each, that is the flaps in this case had not only a control but also stabilizing function. The external views of rated models 1-4 with the same as of experimental models geometry are shown in Fig. 1. The model separating in flight into two constituent parts [8] was referred to the second type. In the initial assembled state the back part of a model (block) having a base diameter D = 60 mm was partially inserted into the front part (leader) having a diameter of 0.814D.

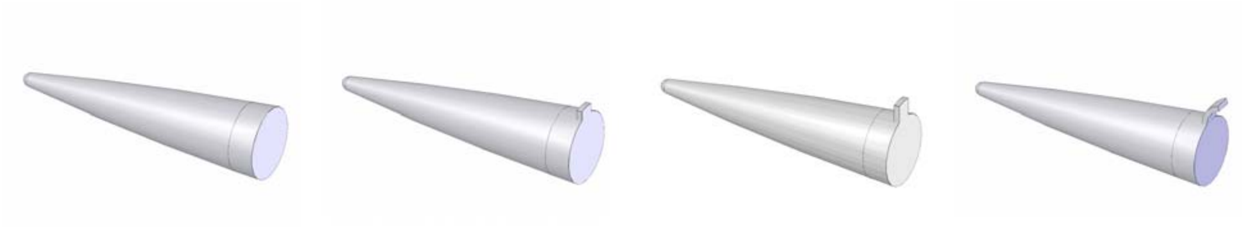
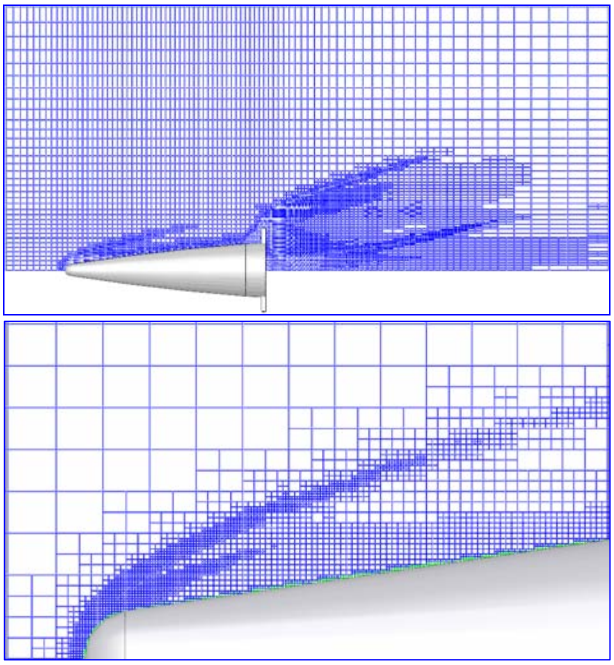


Fig. 1. Models of several hypersonic vehicles considered in the work.

For all specified models, the calculations of their supersonic flow by air under initially normal conditions were carried out. The range of considered initial flow velocities corresponded to a range of Mach numbers from 2 to 6. The range of angles of attack α was within the limits of 10°. The engineering hydrodynamic software program EFD.Lab was used for calculations. The method of numerical solution of the complete Navier-Stokes equations averaged on Reynolds and supplemented by a simple k-ε turbulence model was chosen as a simulation approach. The equation of state of a perfect gas was used for air. As a result of solution the aerodynamic forces and moments acting on a streamline surface of objects and also all the parameters of flowing gas in a calculated volume, namely the fields of pressure, density, temperature and velocity were determined. The complete calculation was divided into several stages, and in the end of each stage the analysis of an obtained solution and the coarse mesh refinement based on this analysis was made in the high-gradient areas of flow parameters. The complete number of counting cells, as a rule, did not exceed $2.5 \cdot 10^6$ in a concrete calculations. The precision of obtained results was estimated by the character of solution convergence on each of the considered stages of calculation. Symmetry conditions were used for the decrease of a calculation domain. In the course of calculation such aerodynamic characteristics of models as the drag coefficient C_x, lift coefficient C_y and pitching-moment coefficient m_z were determined.

In each calculation the principal attention was given to the problems of the adaptation of a countable net and the convergence of a solution with increasing the number of iterations and counting cells generated at each calculation stage. In Fig. 2 the example of a final adaptation of a countable net is shown for the flow pass model 5 with an initial velocity respective to M = 6 after 5 stages of calculation. The first stage of calculation was made on the initial countable net and the subsequent four stages were made on the countable nets adapted after N = 1700, 2550, 3400 and 4250 iterations. The final net presented in Fig 2 consists of 2208346 cubic counting cells. The example of a convergence character of several solutions for models 1 and 5 is shown in Fig. 3 as the change of the drag coefficients with increasing the number of counting cells.



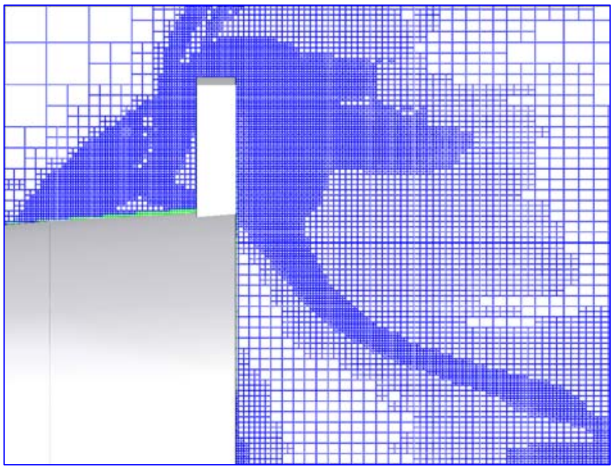


Fig. 2. An adapted mesh when flowing along model 5 with an initial velocity respective to $M = 6$ after 4 rearrangement (N = 1700, 2550, 3400, 4250 iterations) with formation of n = 2208346 counting cells.

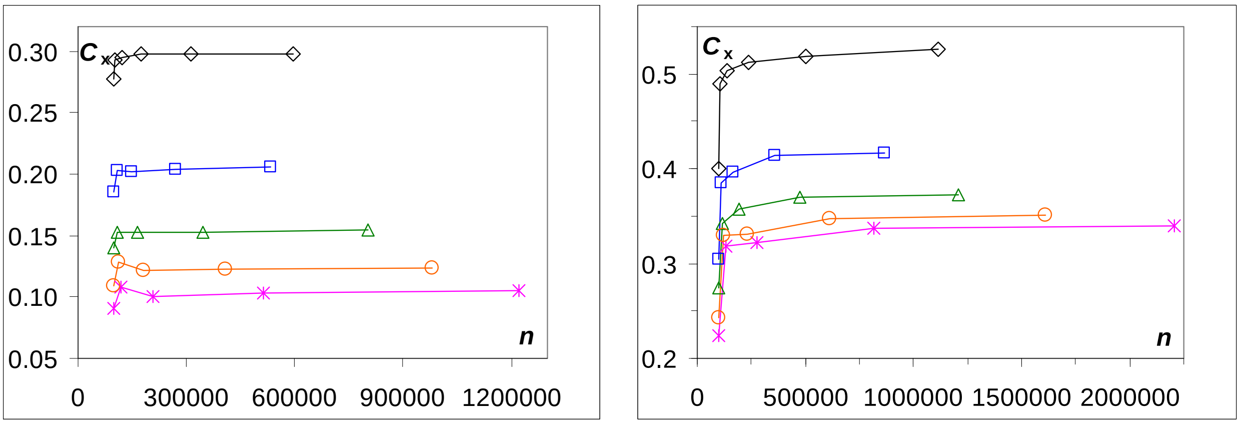


Fig. 3. Change of drag coefficients of model 1(left) and model 5 (right) when increasing the number of counting cells n for $M = 2$ – 6 (rhomb, square, triangle, circle and ж).

CALCULATION RESULTS. The part of obtained calculation results on the supersonic flow pass the models of single-type hypersonic flying vehicles is presented in Fig. 4-15. They are first of all the results on calculated visualization of the process of flow and on the influence of flow velocity on the aerodynamic characteristics of the models. Some of the results obtained for model 1 are given in Fig. 4, 5. The examples of the character of flow pass the basic model without a control flap and the dependences of aerodynamic coefficients on flow velocity and an angle of attack are shown. The results obtained for model 2 with a small flat control flap are given in Fig. 6-8. As an example, in Fig. 8 the distribution of pressure on the back surface of a model for two various flow velocities is shown. The results obtained for model 3 with a large flat control flap are given in Fig. 9-11. Here in Fig. 11 the distribution of pressure on the surface of a model in the vicinity of a control flap is shown for one of the cases of flow. In Fig. 12, 13 and 14, 15 the examples of the character of flow pass the models and the dependences of aerodynamic coefficients on flow velocity and an angle of attack are shown for models 4 and 5. The character of influence of a size and form of control flaps on the course of dependencies of aerodynamic coefficients on flow velocity and an angle of attack was determined on the basis of joint examination of all the results obtained for flapped models. The influence of flow velocity on the values of balancing angles of attack was estimated.

Some of the results obtained for the separating model are presented in Fig. 16-21. Primarily the character of flow pass the initial assembled model and its two constituent parts, the leader and the block, was considered and also the dependences of their aerodynamic coefficients on flow velocity were determined. These results are given in Fig. 16,

17. The results of joint flow past the leader and block for different velocities and distances are given in Fig. 18-21. The character of influence of the distance between the model constituents moving in an axial direction on the course of dependencies of aerodynamic coefficients on flow velocity was determined on the basis of joint examination of all the results obtained for the separating model. For every flow velocity, the distance between the leader and block was estimated, starting from which the change of character of their interaction took place and the block moving in a track began really to come off the leader.

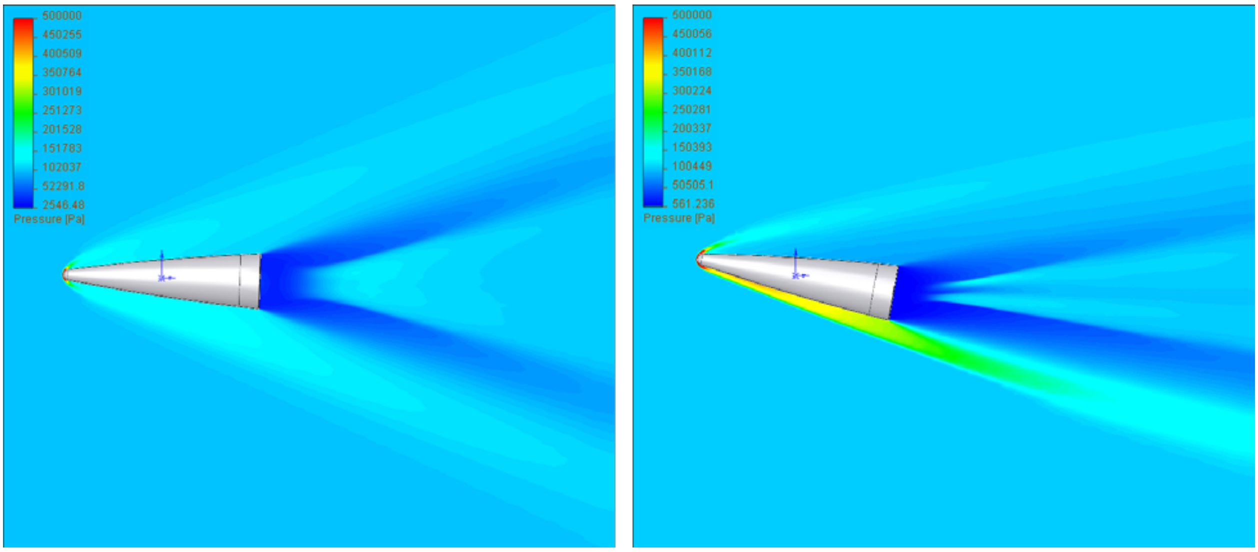
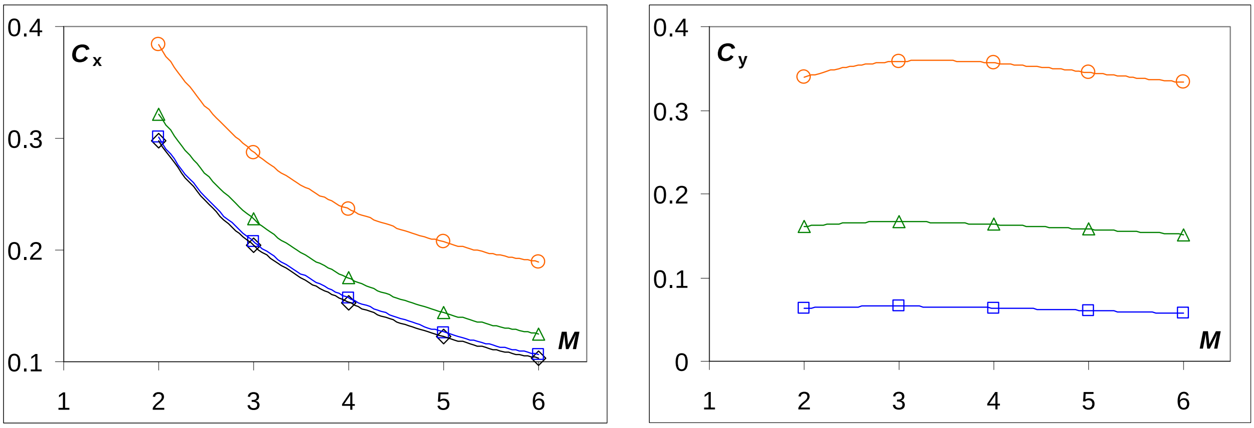


Fig. 4. Flow character of model 1 (pressure fields) for the cases when $\alpha = 2°$, $M = 3$ (left) and $\alpha = 10°$, $M = 5$ (right).



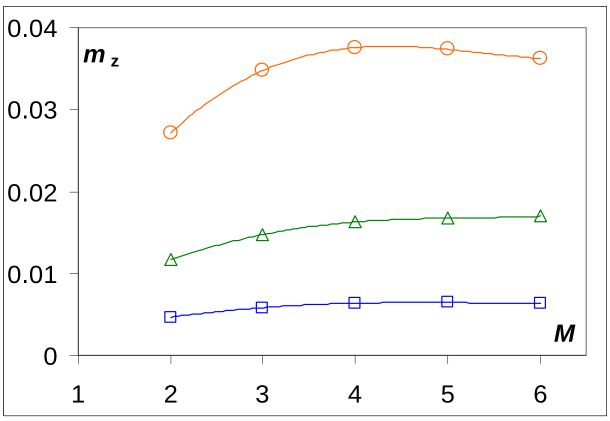


Fig. 5. Influence of a flow velocity on aerodynamic coefficients of model 1 for $\alpha = 0$, 2, 5 and 10° (rhomb, square, triangle and circle).

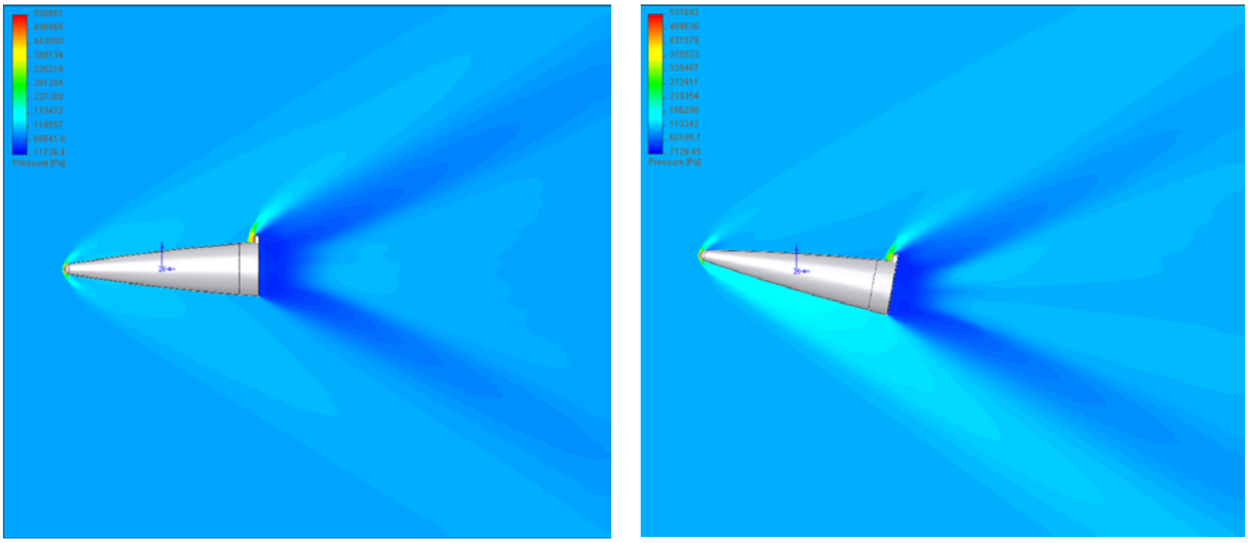
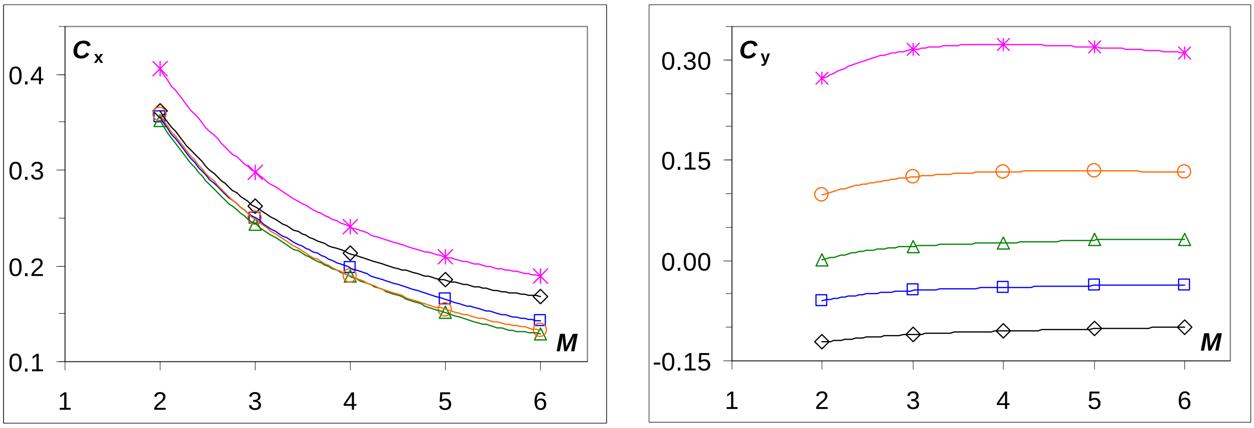


Fig. 6. Flow character of model 2 (pressure fields) for $\alpha = 0°$ (left), $\alpha = 10°$ (right) and $M = 2$.



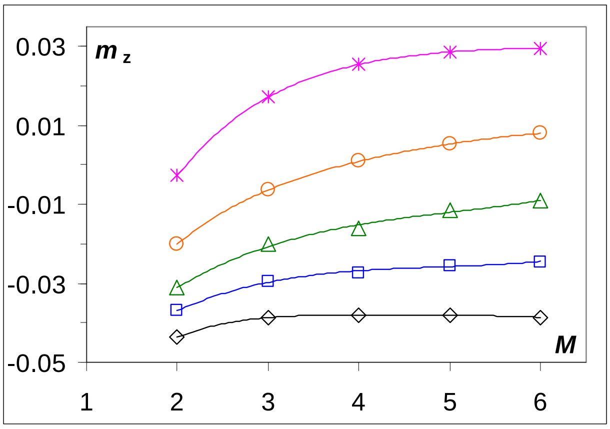


Fig. 7. Influence of a flow velocity on aerodynamic coefficients of model 2 for $\alpha = -2$, 0, 2, 5 and 10° (rhomb, square, triangle, circle and ж).

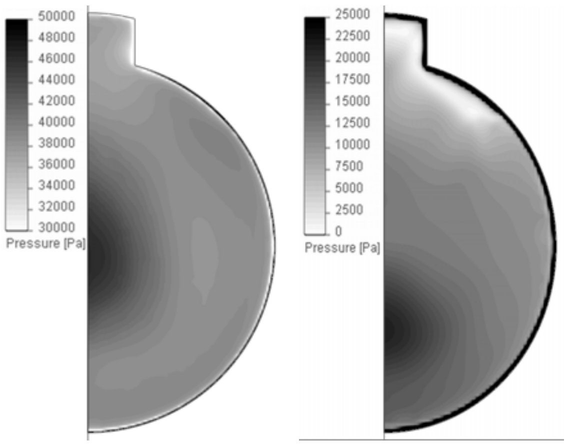


Fig. 8. Pressure distribution on the back surface of model 2 for $M = 2$ (left), $M = 6$ (right) and $\alpha = 0°$.

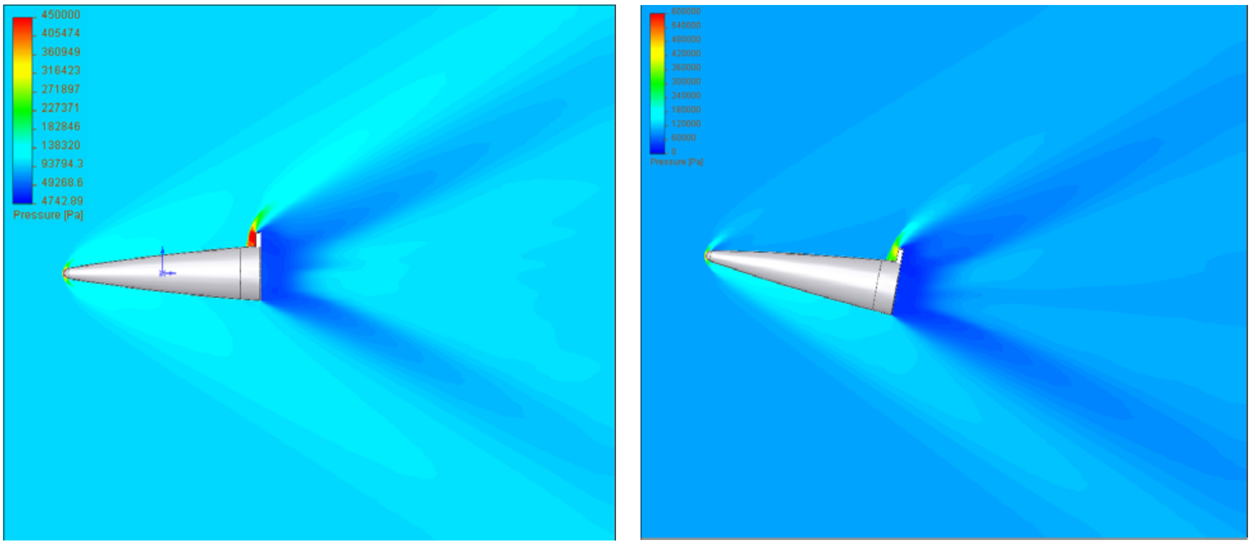
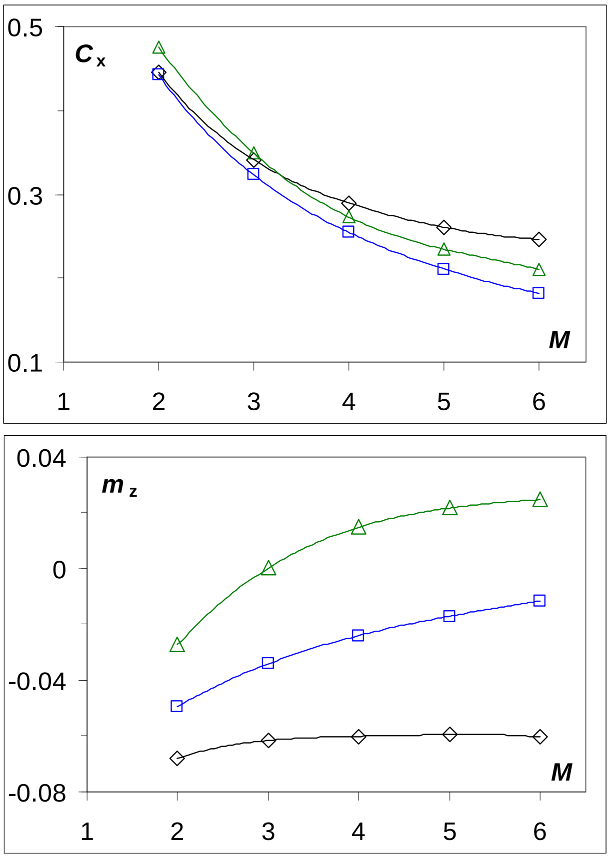


Fig. 9. Flow character of model 3 (pressure fields) for $\alpha = 0°$ (left), $\alpha = 10°$ (right) and $M = 2$.



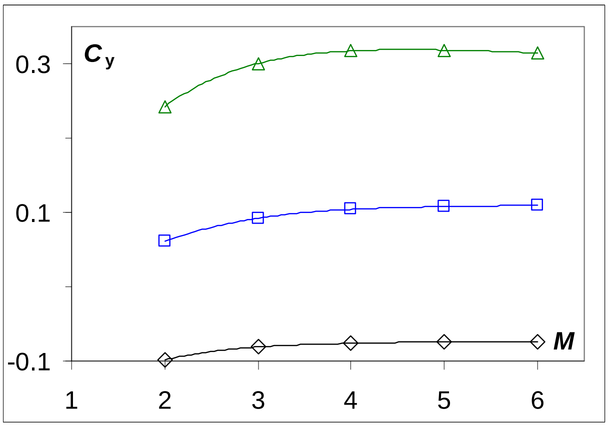


Fig. 10. Influence of a flow velocity on aerodynamic coefficients of model 3 for $\alpha = 0$, 5 and 10° (rhomb, square and triangle).

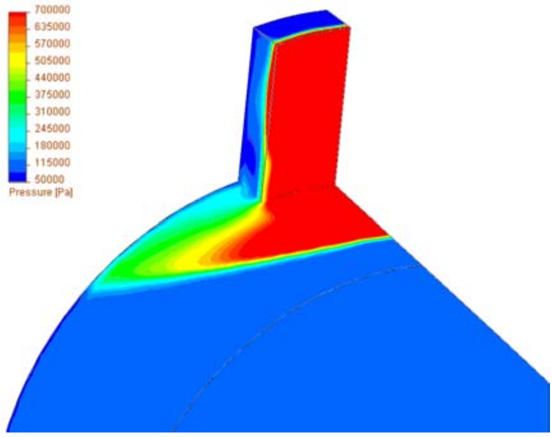


Fig. 11. Pressure distribution on the surface of model 3 near and on the control flap for $\alpha = 0°$ and $M = 4$.

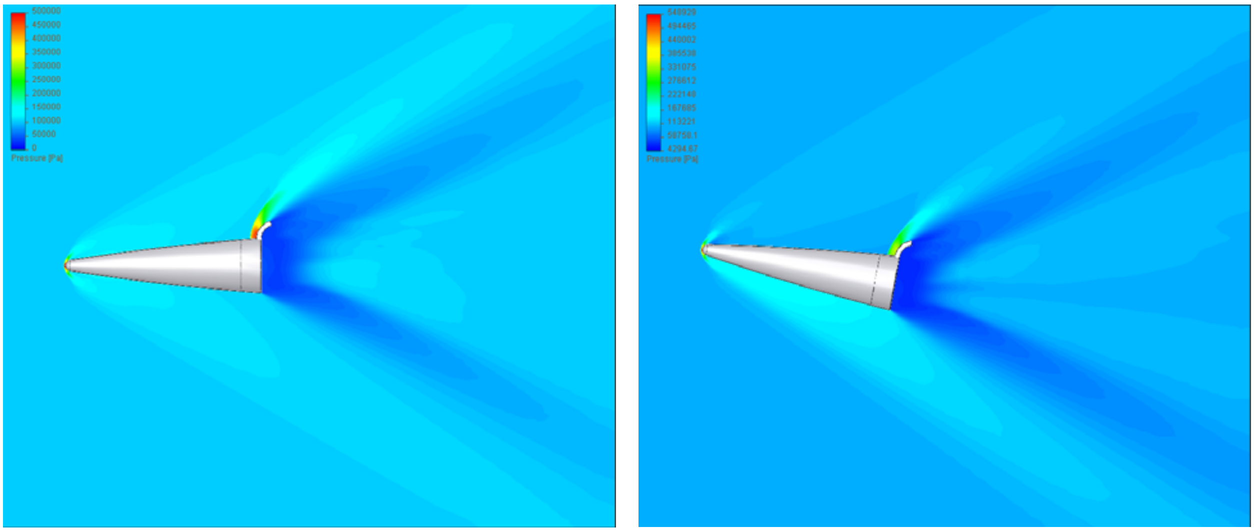
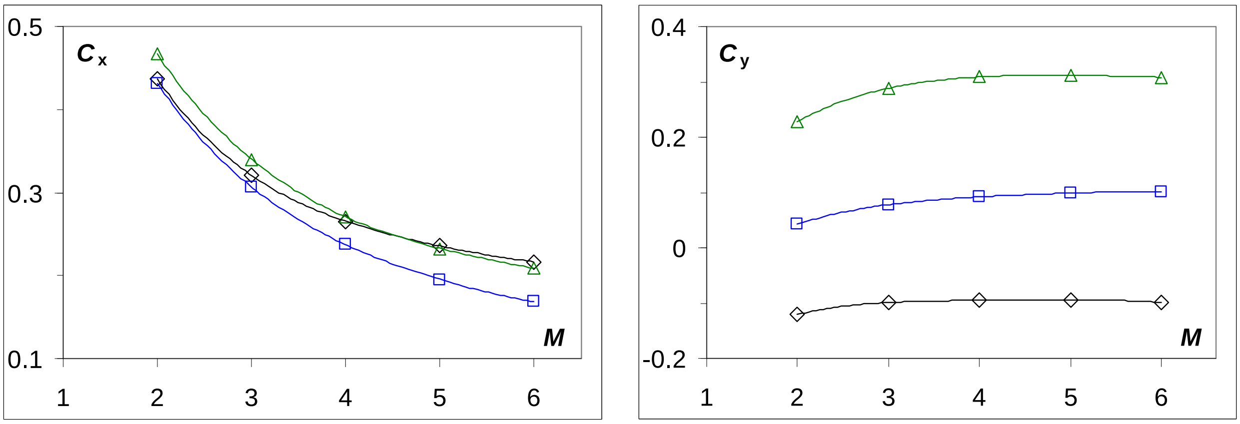


Fig. 12. Flow character of model 4 (pressure fields) for $\alpha = 0°$ (left), $\alpha = 10°$ (right) and $M = 2$.



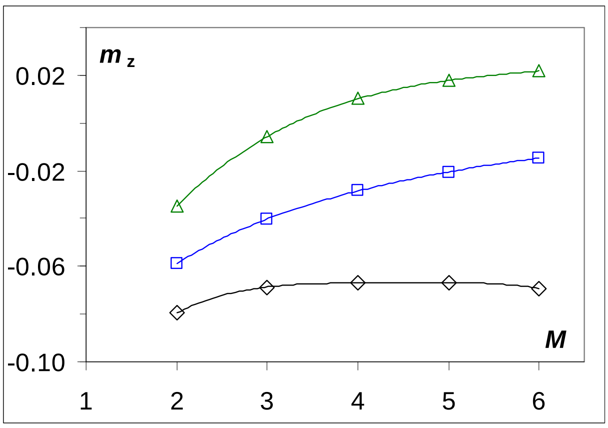
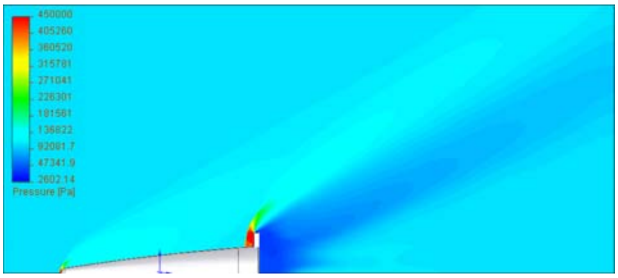


Fig. 13. Influence of a flow velocity on aerodynamic coefficients of model 4 for $\alpha = 0$, 5 and 10° (rhomb, square and triangle).



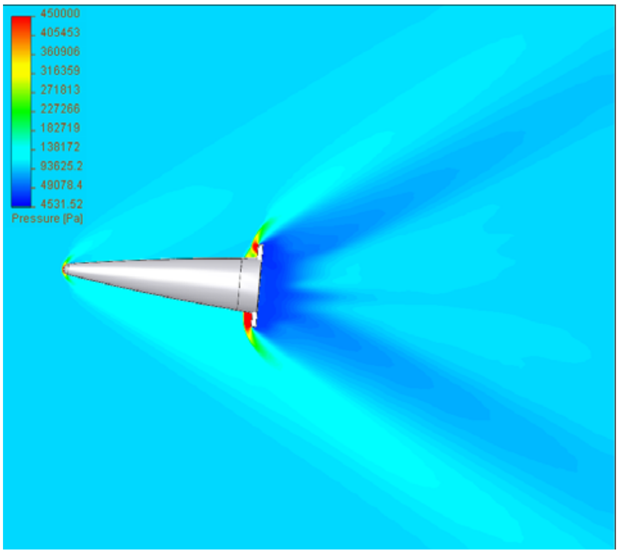


Fig. 14. Flow character of model 4 (pressure fields) for $\alpha = 0°$ (left), $\alpha = 10°$ (right) and $M = 2$.

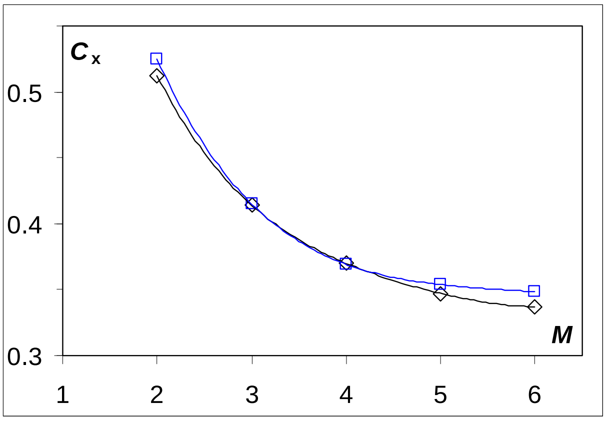
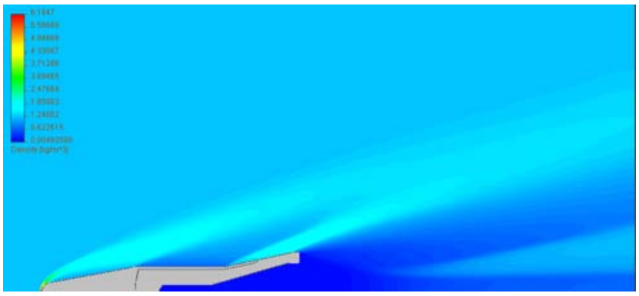
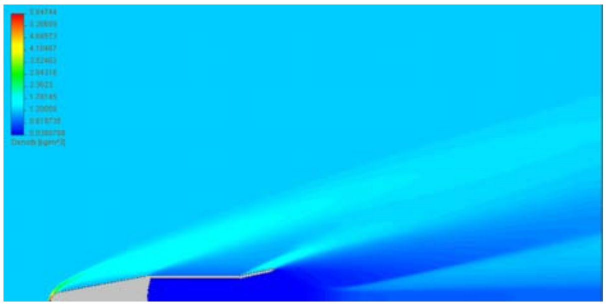


Fig. 15. Influence of a flow velocity on drag coefficients of model 5 for $\alpha = 0$ and 5° (rhomb and square).





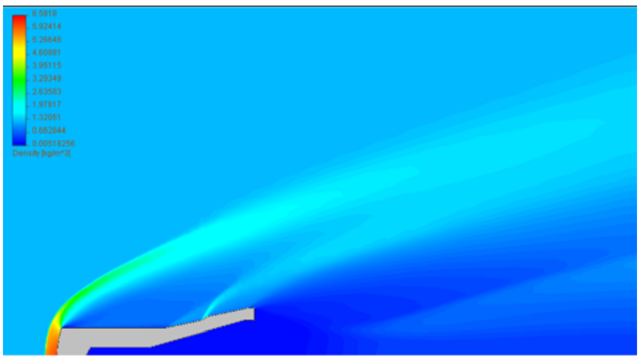


Fig. 16. Flow character (density fields) of the combined model (top, left), leader (top, right) and block (bottom) for $M = 4$.

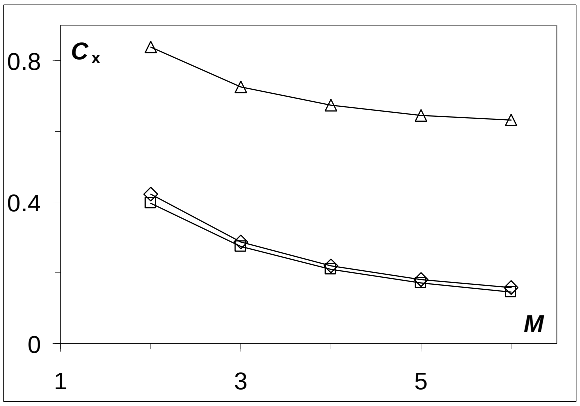
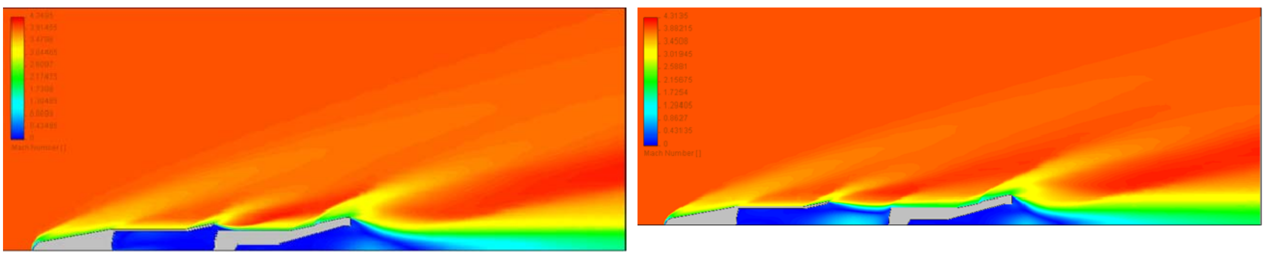


Fig. 17. Influence of a flow velocity on drag coefficients of a combined model (square), leader (rhomb) and block (triangle).



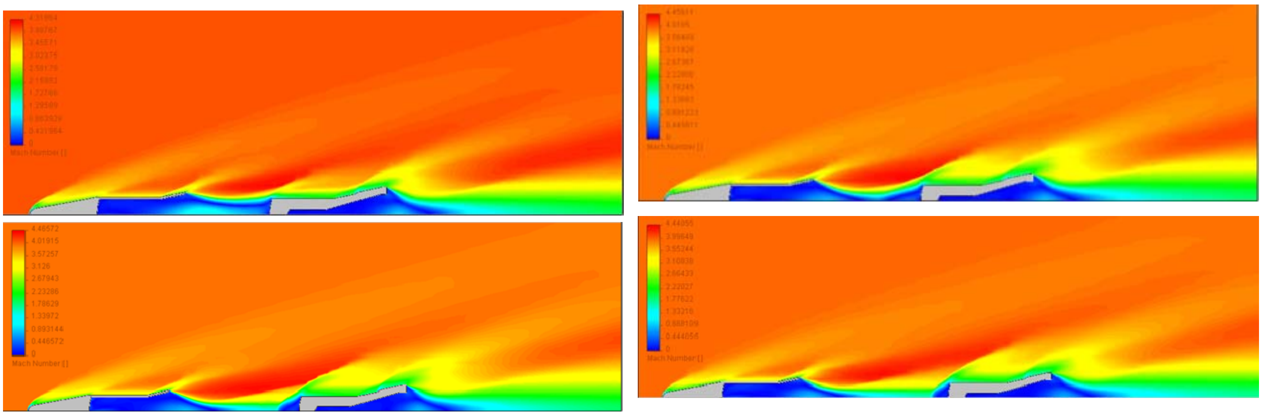


Fig. 18. Joint flow character (Mach number fields) of the leader and block situated at a different distance (Δ = 0, 1, 1.5, 2, 2.5, 3*D* – left to right, top to bottom) at a flow velocity corresponding to *M* = 4.

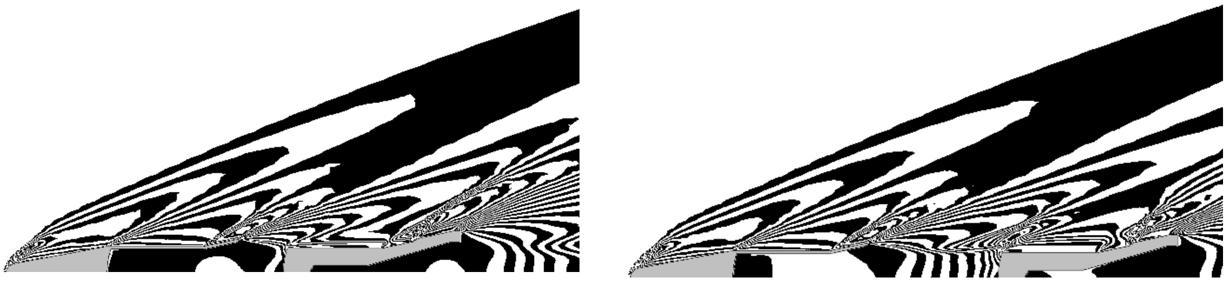


Fig. 19. Joint flow character (density fields) of the leader and block situated at distances Δ = 0.5 (left) and 1.5*D* (right) for *M* = 4 using a different visualization method.

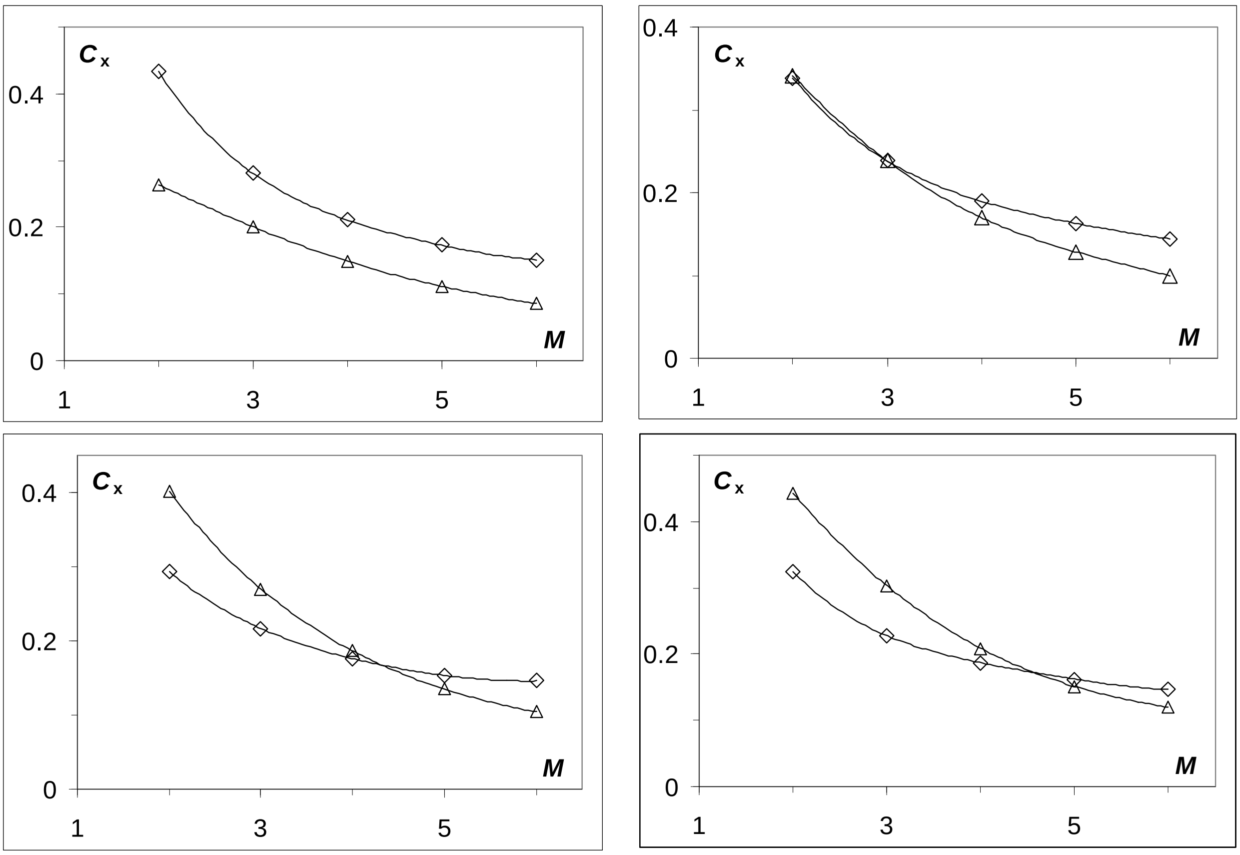


Fig. 20. Influence of a flow velocity on drag coefficients of the leader (rhomb) and block (triangle) situated at different distances (Δ = 0, 0.5, 1, 1.5*D* – left to right, top to bottom) for *M* = 4.

CONCLUSION. The joint consideration of obtained results on visualization of the process of flow and dependences of calculated aerodynamic coefficients of examined models on different factors makes it possible to understand and explain some questions connecting with the influence of models geometry, flow velocity and mutual disposition of models parts on the regularities of supersonic flow past models. In case of examining the supersonic flow past the models with control flaps, the influence of area and form of flaps on the character of flow past the models and on the dependencies of aerodynamic coefficients on flow velocity and an angle of attack was revealed. The possibility of calculated determination of the balancing angle of attack for any flapped model at any supersonic flow velocity was shown. The conducted comparison of obtained calculated results with the separate experimental results given in works [6, 7] points to their rather good agreement and confirms the suitability of the presented calculation method for the tasks of forecasting the aerodynamic characteristics of models with control flaps.

In the case of examining the supersonic flow past the separating model, the influences of distance between its constituents on the character of their joint flow and on the dependencies of aerodynamic coefficients on flow velocity was revealed. The possibility of calculated determination of the distance between the leader and block, starting from which the change of character of their interaction took place and the block moving in a track began to come off the leader, was shown. The conducted comparison of obtained calculated results with the separate experimental results given in work [8] points to their rather good agreement and confirms the suitability of the presented calculation method for the tasks of forecasting the aerodynamic characteristics of separating models. The results of experimental visualization of the supersonic flow past the considered models with use of the shadow method of optical recording are also presented in work [9] along with the considerable quantity of similar results for the other models tested in the aeroballistic shooting gallery.

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