INVESTIGATION OF A TURBULENT BOUNDARY LAYER ON A HYPERSONIC AIRCRAFT MODEL

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An algorithm for calculation of a spatial compressible turbulent boundary layer on the surface of a pointed body is developed. The algorithm is based on the numerical solution of three-dimensional equations and algebraic models of turbulence. The flow around a hypersonic aircraft model is calculated, and the resultant Stanton numbers are compared with experimental data. The influence of the Mach number, the angle of attack, and the Reynolds number on the boundary-layer parameters is studied. It is shown that the change in the location of the transition zone has a weak effect on the skin-friction coefficient in the region of developed turbulent flow.

1. In the development of aviation and spacecraft technology, an important problem is the study of aerodynamic heating of the aircraft surface and the friction forces whose contribution to the total drag is quite significant, especially for a pointed body at small angles of attack. Two approaches are traditionally used to solve this problem: theoretical and experimental. Measurement results are usually considered to be more correct and are used, in particular, for verification of theoretical (numerical) methods, though direct experiments are rare, and the researcher has to choose a certain model of the phenomenon to calculate the desired parameter. The theoretical approach is constructed on the basis of a certain flow model, which fails to take into account all specific features of the phenomenon. In addition, since the use of numerical methods for solving complex systems of equations can introduce its own errors, verification of an algorithm requires a comparison of the results obtained by this algorithm with calculations based on different models and with experiments.

One of the advantages of the theoretical approach is the possibility of calculating all the flow parameters simultaneously, whereas only one parameter is generally measured experimentally. Moreover, in hypersonic flow studies one should take into account that none of the wind tunnels existing in the world reproduces the full-scale stagnation temperature and, hence, does not fully simulate the thermal processes. The advantages of the numerical approach are also the simplicity of variation of the governing parameters (within the validity of the chosen model), the rapid obtaining of new results, and the low cost of calculations as compared with experiments.

The most complete model that describes various flows is the model based on the full Navier–Stokes equations, which were used to obtain the flow around a number of bodies [1–8]. The first two papers are focused on two-dimensional flows around blunted bodies and airfoils, and the remaining papers deal with three-dimensional flows. Isolines and pressure distributions over the body surface are presented in all papers as the numerical results, and only Radespiel and Swanson [2], Herrman et al. [3], and Schröder and Hartmann [5] give skin-friction coefficients or Stanton numbers. The latter, however, are not compared with the results of other authors and experiments, and this is not incidental.

The system of the full Navier–Stokes equations is elliptical, and marching methods of calculation relative to any physical variable are incorrect for it. A fourth variable, the time, is usually added for
convenience. The problem becomes parabolic and is solved by the pseudo-transient method, but only advanced supercomputers can cope with this four-dimensional problem for spatial bodies.

In solving the Navier-Stokes equations for flows with real Reynolds numbers \((10^7 - 10^8)\), large gradients of the flow parameters near the wall should be taken into account. A precise calculation of turbulent flow requires not only several dozens of points of the difference scheme across the boundary layer, but also several points (4–6) in the laminar sublayer. Only in this case is it possible to obtain skin-friction coefficients and Stanton numbers on the surface with an acceptable accuracy. However, this condition imposes stringent requirements on the number of steps and extension of the normal coordinate and is not always observed. Obviously, that is why most papers demonstrate the general pattern of the flow and the pressure distribution over the surface, since these results are the least sensitive ones to the mentioned requirement. Practically no one takes the risk of comparing the skin-friction coefficients and Stanton numbers with experimental data in the above-mentioned papers.

Apart from the full Navier-Stokes equations, parabolized (simplified) Navier-Stokes equations where viscous terms along the marching coordinate are omitted [9–12] and viscous shock-layer equations with viscous terms only normal to the surface are left [13–17] are frequently used to calculate spatial flows. The advantage of these approximations (conservation of all terms of the Euler equations) turns out to be simultaneously their drawback. These equations remain elliptical in the near-wall subsonic regions, which allows an upstream propagation of the perturbations. Thus, the marching method can be used only after applying some "regularization" in the near-wall region. It remains unclear, however, what errors are introduced by "regularization" to the flow parameters in this region, in particular, to skin-friction coefficients and Stanton numbers calculated by differentiation of velocity and temperature profiles in the near-wall region.

The requirement concerning the number of points across the turbulent boundary layer and in the laminar sublayer for these models is also imposed in these papers, but not everywhere fulfilled. It seems that the calculated skin-friction coefficients or Stanton numbers are compared with experiments only in [13, 14, 17].

Another drawback of simplified Navier-Stokes equations is the absence of rigorous mathematical justification in the sense of a certain asymptotical theory. In addition, there is some arbitrariness in choosing the marching coordinate and, hence, the probability of some uncertainty in the solution, which cannot be estimated a priori. In this aspect, the boundary-layer theory proposed by Prandtl [18] and justified by Van Dyke [19] is a rigorous asymptotic theory for high Reynolds numbers, and the higher the Reynolds number, the more accurate the description of a real flow. Because of their parabolicity, the boundary-layer equations can be solved by the marching method, and the requirement on the number of points in the crossflow direction is quite feasible even for medium-class computers, since the solution is constructed separately in a narrow near-wall region.

The drawback of the boundary-layer model is that it cannot be used independently. The boundary-layer equations require all the flow parameters at the external boundary to be known, except for the normal component of the velocity, which can be found experimentally or numerically from inviscid calculations. The conditions at the external boundary should be determined very accurately, since their error increases with solution of the boundary-layer equations using these conditions. The wetted surface should be also described rather accurately by a certain smooth function with continuous second derivatives, which enter the coefficients of these equations.

Based on the aforesaid, we chose the classical Prandtl model [18] to study the flow around a hypersonic aircraft. In this model, the flow between the body and the shock wave is divided into an inviscid region and a thin boundary layer. The Euler equations were solved for the first region and the spatial boundary-layer equations for the second region.

2. There are some papers devoted to the study of a laminar boundary layer on pointed elliptical cones at high [20–24] and low angles of attack [25, 26]. For these bodies, experimental values of the Stanton number \(St\) were obtained [27]. For high angles of attack, the divergence line is typically located on the cone surface in the plane of symmetry, where the maximum values of the skin-friction coefficient \(c_f\) and \(St\) are observed. For small angles of attack, the divergence line can be located outside the plane of symmetry, and the maximum values of \(c_f\) and \(St\) coincide with neither of them. A spatial flow around a pointed bielliptical body was