REGIMES OF LAMINAR LATERAL FLOW SEPARATION DUE TO JET EXHAUST

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Numerical simulation of the separation flow on the lateral surface of an aircraft due to interaction between the engine exhaust plume and the external air-stream is carried out on the basis of the full Navier-Stokes equations. Three separated flow regimes are revealed, namely, closed, open and periodic. The conditions under which each of these three regimes may exist are determined.

A region of separated flow on the lateral surface of an aircraft can arise in flight at high altitudes due to the interaction of the engine exhaust plume with the outer air-stream. This region grows as the aircraft ascends. The dependence of the gasdynamic and geometric parameters of the separation region on the parameters governing the free stream and the jet flow has been determined in [1-5] and elsewhere, both experimentally and theoretically. As a rule, those studies were carried out for small values of \( n = \frac{p_a}{p_s} \), the ratio of nozzle to ambient pressure. The formation of closed flow separation regions with subsonic speeds inside is characteristic of this case (Fig. 1). The behavior of separated flows at large nozzle to ambient pressure ratios has not yet been established.

The problem of the chemical composition of the gas filling the separation region, or, in other words, the question of the proportion of jet gas penetrating this zone, has not been well studied either. True, the numerical solution of the Navier-Stokes equations, obtained by one of the authors of the present paper, has made it possible — on the basis of the calculated equilibrium temperature distribution — to hypothesize that a large amount of jet gas is present in the separation region at high outer air-stream velocities. Though this hypothesis seems quite plausible, the factual evidence in its favor is still insufficient. This evidence can be obtained directly from the solution of the full gasdynamic system together with the species diffusion equation, by considering flows of different gases in the jet and in the outer stream. Precisely these problems are studied here.

1. The problem of the interaction between the flow past a cylinder and a jet flowing out from its base was considered for the axisymmetric case within the framework of the full time-dependent Navier-Stokes equations. The inverted Osher scheme [6] was used to integrate the system of equations; its order of approximation was raised to second by using flux limiters [7]. The splitting scheme [8] was also used. Only laminar gas flows were studied.

The problem was treated in a rectangular domain of the meridional plane, bounded by the body surface, the axis of symmetry, and two surfaces located sufficiently far from the separation region, so that the boundary conditions on these surfaces do not seriously affect the flow inside the separation zone (Fig. 1). The parameters of the outer flow with a viscous wall layer near the lateral surface were prescribed on the windward boundary of the computation domain. The width of the wall layer with a sinusoidal velocity profile was taken to be \( 0.2r_a \), where \( r_a \) is the nozzle exit radius; this radius, which is taken as a scale length, is designated by the letter \( D \) in Figs. 1-4. The no-slip condition was assumed on the lateral and base surfaces, while the conditions of smooth flow matching were prescribed on the windward and upper boundaries. The jet parameters were prescribed at the nozzle exit. The radius of the cylinder was \( 1.18r_a \).

The gases in the outer stream and the jet flow were taken to be perfect, with different thermal properties; namely, specific heats at constant pressure \( c_{ps} = 1.004 \text{ kJ/(kg-deg)} \), \( c_{pa} = 1.84 \text{ kJ/(kg-deg)} \); specific heat ratios \( \gamma_s = 1.4 \), \( \gamma_a = 1.17 \); static temperatures \( T_s = 256^\circ\text{K}, T_a = 1880^\circ\text{K} \).

The Mach numbers of the outer stream and the jet flow were taken to be \( M_s = 6 \) and \( M_a = 3.8 \). The subscripts \( s \) and \( a \) refer to parameters of the outer stream and the jet flow, respectively. The nozzle to ambient pressure ratio \( n \) was varied over the range \( 10^2-10^5 \), and the Reynolds number based on the outer stream parameters was taken to be \( Re_s = 3300 \).

The flow parameters, both simulating and not simulating the starting of an engine, were prescribed as the initial data in the computation domain. However, after a number of time steps the solutions became identical in both cases. Most of calculations were

carried out with initial data simulating starting conditions.

The calculations were carried out in a domain measuring $40r_a \times 16r_a$, with up to 12,000 grid points ($134 \times 109$, $72 \times 62$, $51 \times 51$, and $36 \times 31$), on essentially nonuniform networks with maximum grid condensation near the lateral surface of the body and in the vicinity of its base, i.e., in the regions of greatest change in the flow parameters. The mesh sizes in both directions grew uniformly with increasing distance from the body surface and the nozzle exit. The solutions calculated using different networks are in agreement, and converge with diminishing mesh size.

2. The calculations were continued until a steady-state or a periodical solution was obtained. In order to establish this moment, the variations in the general flow pattern and the separation flow parameters with time were monitored. The solutions obtained by both methods (i.e., by the Osher and splitting methods) were in agreement. Most of the results presented were obtained by means of the former method.

In what follows, the results characterizing the separated flow will be presented. First of all, we note that calculations carried out at $M_j=6$, $M_a=3.8$ for various nozzle to ambient pressure ratios revealed the existence of three separated flow regimes near the cylinder surface, namely, closed, open, and periodic.

Separated flow of the closed type exists when the nozzle to ambient pressure ratio $n \leq 10^3$; it is characterized by the presence of two or three nearly steady-state vortices in the separation region (forward, central, and rear) with subsonic speeds inside. Figure 1 presents the streamlines corresponding to $n=10^3$, $M_j=6$, $M_a=3.8$. The central vortex is the smallest and sometimes does not appear at all. The forward vortex is the greatest, occupying up to 90% of the whole separation region. At $n \leq 10^3$ the forward vortex is purely internal, or closed, i.e., it has no channels of convective mass exchange with the outer and jet flows. The rear vortex is considerably smaller; it acts as a valve separating the forward vortex from the jet flow and metering the mass exchange between them. It has a channel of mass exchange with the outer flow; therefore it is open. However, the velocities in the channel throat (i.e., in its narrowest cross-section marked by arrows in Fig. 1) are small. Therefore, the gas exchange between the rear vortex and the outer flow is not very great.

The pressure in each cross-section of the separation region (in the forward vortex) is practically constant. As established above, a pressure "plateau," or domain of constant pressure, extends along the side wall in the separation region. The greatest pressure gradients occur near the right-hand boundary of the rear vortex and in the vicinity of the separation point.

The jet flow gas enters the closed separation region mainly as a result of diffusion (except for the early stage of transition to the steady state). Since the part of the separation region washed by the outer stream is much larger than that washed by the jet flow, the separation region is mainly filled by gas from the outer flow, i.e., by air. The average mass proportion of jet gas is smallest in closed separation regions, as compared with separation zones of other types, having a value of about 0.15. The local proportion of jet gas is greatest in the region where the separation zone touches the jet flow and in the vicinity of the lateral surface; in these regions it varies from 0.7 to 0.3.

The open separation region appears with further increase in the nozzle to ambient pressure ratio $n$; it exists when $n$ varies over the range from $3 \cdot 10^3$ to $7 \cdot 10^3$. Its characteristic feature is the presence of two vortex zones, namely, a small rear zone with a closed vortex and a large forward one with a vortex which is open to the jet gas (see Fig. 2 which shows the streamline pattern for $n=5 \cdot 10^3$). In a few cases a small central vortex appears, which influences the separated flow only slightly. The jet gas finds