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VORTEX FLOWS WITH SUSPENDED SEPARATION REGIONS AND LONG-RANGE UNTWISTED CENTRAL JETS

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A study is made of possible physicoaerodynamic configurations of vortical flow with suspended separation regions and untwisted central jets. Such flows are encountered in power plants (combustion chambers, heat exchangers, chemical reactors, etc.) and in nature (tornadoes).

Special vortical flows with suspended separation regions and long-range untwisted jets occur in power plants — such as in certain types of heat exchangers, separators, high-speed combustion chambers, and chemical reactors — and in nature. The development of a theory of such flows needs to be backed up by qualitative experimental studies of the corresponding initial aerodynamic schemes.

This article is an attempt to describe the basic configurations of several flows of this type. The configurations may be useful in constructing methods of theoretical calculation.

1. Structure of a Flow Formed by Coaxial Cocurrent Twisted Jets. Coaxial cocurrent jets are employed in high-speed combustion chambers, chemical reactors, and mixers. Such flows have been studied in detail for the case of the absence of preliminary twisting. An example is the study in [1] with reference to ejectors.

Many investigations have focused on the case of a central twisted jet [2]. It was shown in [2] that a suspended separation region forms at the beginning of the central jet for sufficiently intense twisting. S. Yu. Krasheninnikov proposed a dimensionless criterion for the formation of this region. Quantitative studies have also been made of the case when both jets are twisted [3, 4]. However, no one has yet come up with a clear scheme for the formation of suspended separation regions in flows of this type. Nonetheless, suspended separation regions are necessary in high-speed combustion chambers to stabilize the flame and organize a stable diffusion front for the flame.

There are four cases in which suspended separation regions can be formed: 1) the jets are twisted in opposite directions; 2) the jets are twisted in one direction; 3) only one jet is twisted; 4) neither jet is twisted.

The translational velocities in jets 1 and 2 (Fig. 1) are usually different ($u_{1a} \neq u_{2a}$). The presence of twisting is connected with a reduction in pressure toward the axis of the

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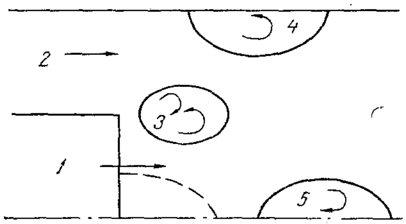

Fig. 1

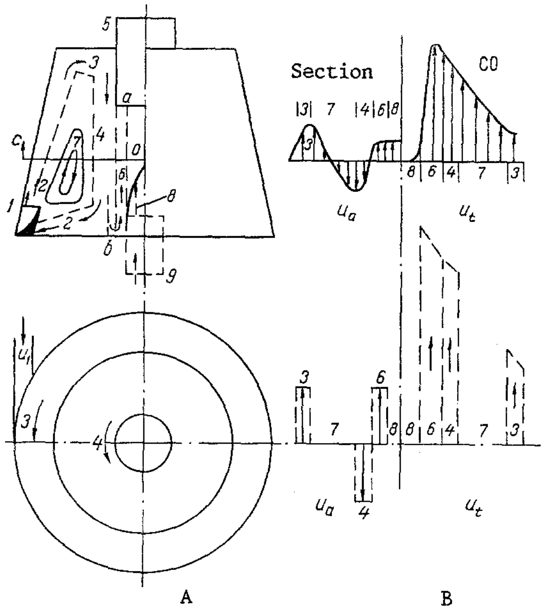

Fig. 2

Fig. 1. Suspended separation regions: 1, 2) jets entering the chamber; 3) suspended toroidal separation region; 4) separation region near the wall of the mixing chamber; 5) suspended axial separation region.

Fig. 2. Flow pattern in a conical swirl chamber (A) and the velocity field (B): 1) tangential feed of gas into the chamber; 2, 6) rotation of flow at the large base; 3) rotation of flow at the small base; 4) incident flow; 5) outlet pipe (nozzle); 7) internal separation region; 8) core; 9) central pipe.

flow. Equalization of the field of axial velocities and untwisting of the flow under the influence of eddy viscosity are accompanied by an increase in pressure (with increasing distance from the beginning of mixing). In turn, the positive pressure gradient generates a suspended toroidal separation region 3 in the zone of confluence of the boundary layers flowing from the internal and external walls of the channel of the central jet. If the velocity of the external jet is lower than the velocity of the central jet, a region of flow separation 4 from the wall of the mixing chamber may also form.

If the twisting of the central jet is very substantial or if its velocity is much lower than the velocity of the external jet, a suspended axial separation region 5 develops. This region has been described both in the presence of twisting [2] and in its absence [1]. Figure 1 shows the most general flow pattern, with three separation regions. In the case of strong twisting of the central jet, the beginning of the axial suspended separation region 5 is located at the end of the channel 1 of the central jet (dashed line), and region 5 precedes region 3. The specific conditions for the formation of each of these separation regions and for formation of the flow as a whole when the regions are present can be approximately calculated by resorting to current representations of the applied hydrodygasdynamics of turbulent flows, with the use of certain empirical constants or auxiliary functions. Such a calculation is simplest for region 4 and most complicated for region 3.

In the case of two jets having angular momenta of the same magnitude but different signs, a flow regime in which an untwisted axial jet is formed is possible.

2. Description of Flow in a Conical Swirl Chamber with the Formation of an Untwisted Long-Range Axial Jet. A scheme depicting the complex flow in such a chamber was first proposed and studied by R. S. Trofimov [5]. The aerodynamic configuration of the chamber and the presumed velocity fields in it are shown in Fig. 2A. Compressed air enters under high pressure at a high velocity u_{1t} through a plane slit 1. It is directed tangentially relative to the lateral surface of the chamber and has the form of a truncated cone. The outlet pipe 5 is located in the small base of the chamber. The cross section of the chamber is considerably larger than the cross section of the inlet slit. Thus, the narrow jet 1 spreads over the internal surface of the cone, having a high circumferential velocity u_{1t} and a low translational velocity u_{1a} (in the direction of the small base). The latter is

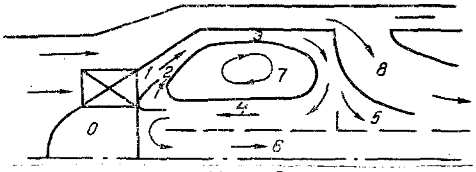

Fig. 3

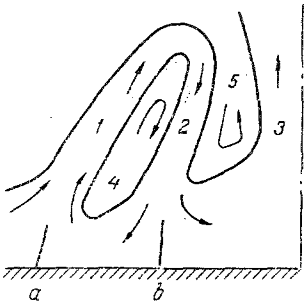

Fig. 4

Fig. 3. Flow pattern in the chamber of a gas-turbine engine: 0) swirler; 1) jet entering the chamber; 3) diversion to jet 1; 3) forward jet; 4) annular reverse jet; 5) diversion to mixing zone; 6) axial jet; 7) separation region; 8) secondary air jets.

Fig. 4. Structure of the flow of a tornado; 1) ascending (convective) flow; 2) descending flow; 3) central jet; 4, 5) separation regions (suspended); a) zone of encounter of two jets; b) zone of encounter of the annular jet and the surface.

determined by the volume flow rate of the gas at the inlet V_1 and the annular cross section of the jet.

The dashed line in Fig. 2A shows the boundary of the jet which might exist in an ideal fluid (where the molecular and eddy viscosities are ignored). In this case, a significant portion of the volume of the chamber 7 is filled by a stationary medium with a constant pressure. The medium exerts a lower pressure on the chamber wall (due to the centrifugal force). It follows from the condition of conservation of circulation that there is a constant value of translational velocity (Fig. 2B) $u_{a1} = u_{a3} = u_{a4}$ in a jet of ideal fluid and an increase in its thickness with motion along the generatrix of the cone toward the axis of the small base. This direction of motion is the result of a reduction in pressure on the wall of the cone, which is in turn caused by a reduction in the radius and a corresponding increase in rotational velocity (with a constant value of circulation). After rotation (from its encounter with the nozzle 5 in section 4), the jet of ideal fluid separates from the edge a and, maintaining its annular cross section, reaches the large base. Here, over a circle of the radius r_b, the jet is separated into two parts. One part 2 flows to the periphery of the large base and merges with the jet 1. The other part 6 changes to the opposite direction and approaches the outlet opening 5. A vortex surface of strong tangential discontinuity develops at the boundary between jets 4 and 6.

It follows from the above figure that part of the fluid 2 completes a closed motion inside the chamber. The sign and magnitude of the velocity circulation remain the same ($\Gamma_3 = \Gamma_4 = \Gamma_1$) in the transition of the jet of ideal fluid from section 3 to section 4 and from section 4 to section 6, but a core of stationary fluid 8 with a pressure equal to the pressure at the chamber outlet ($p_8 = p_5$) develops in the central jet. Due to the small radius of rotation, pressure is lower on the inside surface of the jet 6 and in the core 8 than in the cavity 7. This is related to the corresponding increase in rotational velocity. With a specified pressure difference ($p_1 - p_5$), the discharge of ideal fluid through the above-described cone is determined in the same manner as for a swirl injector [6]. In changing over to an actual flow in the chamber (with allowance for the effect of eddy viscosity), it is necessary to consider the presence of the boundary layer on the walls and the mixing layers on the boundaries of active flow with region 7. Flow in the counter motion of jets 4 and 6 and on the boundary of the core 8 must also be taken into account here.

Figure 2B (dashed lines) shows the character of the profiles of the translational u_a and rotational u_t components of velocity in the cross section of an actual chamber and in the case of an ideal fluid.

In an actual flow, region 7 is an internal separation region with closed translational motion of the added masses and rotational motion in one direction. However, the rotation occurs with different velocities, in accordance with the rotation in jets 4 and 3.

Fig. 5. Photograph of a tornado: B) near-surface region of flow subdivision.

As is known [7], large, nearly linear velocity gradients in the layer separating jets 4 and 6 lead to suppression of eddy diffusion. In connection with this, the jet 6 – in which the residual circulation is very small ($\Gamma_6 \ll \Gamma_4 \ll \Gamma_1$) due to viscosity – approaches the small radius nearly without rotation, while the core 8 disappears, i.e., only translation motion remains in the jet 6 before the nozzle has been reached. If we add a central pipe 9 to the chamber (shown in Fig. 2A) and use it to supply the chamber with gas of a different composition or temperature but the same velocity, then the gas jet 8 passes through the chamber and mixes only slightly with the ambient air, i.e., with negligible convective heat and mass exchange between it and the ambient air.

It is evident that the air will be mixed with the central gas jet only directly ahead of the nozzle 5 and after the nozzle. When this is undesirable, mixing can be avoided if we provide the conical body of the chamber with additional air sinks through two annular slits: at the periphery of the large base of the chamber and in the small base (with the radius of the annular slit greater than the radius of the nozzle). This effect was first noted by R. S. Trofimov in tests in which he observed that the velocities of axial flow of the air and gas are connected by a dual linear relation. The relation initially increases with an increase in flow rate and has a maximum at roughly equal values of these velocities. It then decreases at very high flow rates. The velocity maxima for different air flow rates lie on one straight line, which is evidence of the self-similar nature of the flow in the chamber. In the regimes corresponding to the descending branches of the curves just described, mixing of the central region is intensified and the region becomes shorter and less stable.

In connection with the above, it is interesting to examine a device for the heating of a fluid such as water by hot air or combustion products [5]. The basic flow pattern in such a device corresponds to the pattern shown in Fig. 2A, but a jet of water is delivered through the central opening 9 instead of gas. With suitable twisting of the air flow, the vertical water jet passes through the conical chamber without mixing with the vortical air flow. In the case of very substantial twisting of the air flow or a very low velocity of the water jet, the stability of the jet is disturbed and it breaks up into drops a certain distance from the inlet opening. These drops are intensively heated by the gas and are moved by centrifugal force to the lateral wall of the chamber. There, the drops form a stable sheet of water. The drops also form a hydraulic seal at the outlet of the conical body, which in the given case leads smoothly into the outlet pipe. The heated water leaves the chamber through this pipe, while the gas or air leaves through an annular slit at the wide base.

A phenomenon similar to that just described has repeatedly been observed in the combustion chamber of jet engines equipped with a swirler [8]. However, no explanation for the phenomenon has been offered until recently. Nevertheless, the flow scheme described above is very close to that in the initial part of the combustion chamber (Fig. 3), where some of the air is brought into the primary zone through the swirler 0.

The twisted annular air jet 1 leaving the swirler 0 forms the separation region 7. Colliding with the secondary air jets issuing from the annular channel into the firetube through the hole in its wall, the axial jet is then directed toward chamber axis. Here, the jet is separated into two parts, one of which 5 is entrained by the secondary jets into the mixing zone of the chamber. The second part forms a twisted annular reverse jet 4 which is weakened by viscous forces. The second part is itself divided into two parts near the base of the swirler. The first jet 2 which results from this subdivision merges with the jet 1, while the second jet 6 is directed toward the mixing zone. The jet 3, consisting of jets 1 and 2, is rotated in one direction along with the reverse jet 4. However, due to friction in the boundary layers and on the boundaries of separation region 7, velocity circulation is lower in jet 4 than in jet 3. Meanwhile, due to friction in the layer separating the axial jet 6 from the jet 4, the former jet may be untwisted. It may also be very long-range, for the same reasons as in the above-described conical chamber [5]. The injection of a relatively small amount of fuel and its combustion should not significantly distort the kinematics of the flow in the primary zone. The creation of a central long-range jet which mixes only slightly with the cooler surrounding medium may lead to the undesirable retention of temperature-field nonuniformity at the end of the combustion chamber.

It is understood that the untwisted long-range jet develops in vortex flow only under special conditions — in particular, under the conditions described above.

3. Some Considerations Regarding the Aerodynamics of a Tornado. Tornadoes can reach considerable heights and carry heavy objects significant distances. This is possible only when the interior of the tornado contains an untwisted, long-range ascending jet of air with a velocity of 50 m/sec or more. If the jet is twisted, then the objects lifted by the tornado will be thrown out of the tornado by centrifugal force. These considerations suggest that the aerodynamic configuration of a tornado is similar to that described in Part 3 for a conical swirl chamber, although there are important differences. A tornado occurs in the presence of tangential discontinuity in a wind flow in the vertical plane. As is known, such a surface is unstable, and it disintegrates with the formation of large and small eddies. The coarse eddies begin to rotate relative to their thin external layer when they are first formed. If the air of this layer is overheated — and tornadoes usually occur in hot climates or during summer — then an ascending (convective) flow 1 (Fig. 4) develops in the tornado. The drop in pressure is balanced by an increase in circumferential velocity, accompanied by a reduction in the radius of rotation.

Thus, the external part of the tornado has the form of a truncated cone with its large base on the surface of the earth or water.

Air is supercooled (due to an increase in its rotational velocity) as it is lifted in the rotating annular external layer of the tornado. The supercooled air becomes denser than the air in the atmosphere around the tornado, and this results in extinction of the velocity of the ascending flow due to a reversal in the sign of the buoyancy force. A fountain effect develops in the case being described, this effect being expressed in the fact that the external annular jet which has built up toward the axis of the tornado begins to descend inside the tornado 2 and form a truncated cone with its large base on the earth or a water surface. The base also has an annular cross section. The absence of condensation nuclei in the two annular jets of the tornado helps retain moisture in the form of supercooled vapor. Thus, these layers are transparent and are not noticeable in ordinary photographs of tornadoes. The descending annular layer of air is slowed and broken up near the ground or water, creating a high-pressure region and lifting particles of dust or water which subsequently become condensation nuclei for the supercooled vapor. Here, heat is liberated. This heat raises the temperature of the air, which moves along the surface in two directions — toward the outer ring of the tornado and toward the axis of the inner ring. The first part of the flow of heated air begins to replenish the outermost convective flow in the tornado, while the axial flow forms a central jet 3. The velocity in this jet is directed upward and may be considerable, due to buoyancy and the initial momentum. Drops which have not fully evaporated or dust particles make the central jet visible (see Fig. 5).

The photograph clearly shows the dust-laden near-surface region B where the flows of air heated by moisture condensation are separated. The presence of friction opposing twisting of the flow helps reduce circulation in the annular layers and particularly in the inner layer, which is separated from the central jet by a thin zone with high transverse velocity gradients.

Moreover, negative pressure, increasing toward the axis of the tornado, acts to draw the nearly untwisted near-surface boundary layer of the wind flow into the central jet. Dust and water droplets also reduce angular velocity. These factors explain the above-noted absence of twisting in the ascending central jet. In experiments, R. S. Trofimov observed a vortex with a nonrotating core in a conical model chamber (the core was visualized by axially introducing bromine vapors into the chamber).

In conclusion, we noted that the existence of high pressure (in the zone where the annular jet meets the surface) and low pressure (in the central jet) is supported by the character of failures which occur in tornadoes (for example, the roofs of buildings are not only pushed in, but are also torn off and carried some distance). A cross wind distorts the axis of a tornado, as is evident from Fig. 5. The flow pattern inside a tornado described here is fairly stable, which helps to conserve it as the tornado is transported tens of kilometers by the wind flow.

NOTATION

u_a, u_t, translational and circumferential components of velocity of the gas flow; V_1, volume flow rate of the gas; Γ, gas velocity circulation; p, gas pressure; r, radius of the cross section.

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NUMERICAL MODELING OF COMPLEX VISCOUS FLUID VORTICAL FLOWS

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The influence of the turbulence model, numerical diffusion, and methods of formulating the boundary conditions on a solid wall on computation results is analyzed in an example of a finite-difference simulation of viscous fluid vortical flows in a broad range of Mach and Reynolds number variation.

Despite the success in applying electronic computers to solve different fluid mechanics and heat and mass transfer problems, the relation to the information, obtained as a result of such a computational experiment, for potential consumer-specialists in the design of new engineering is still extremely cautious if not generally negative in many cases. To a considerable extent this is explained by the designers of engineering not being prepared to perceive the idea of a computational experiment, which is due not only to the majority not having experience in working by using an electronic computer but also to the constraints of purely computational nature on the applicability of the computation results, which are governed by features of the numerical procedures constructed, the turbulence models selected, the boundary conditions formulated, etc.

In this paper, the available relationships of the possible defects and difficulties of reproduction of real flow properties in the computational experiment to the mentioned cons-

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