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Variety of gas-dynamic turbulent configurations at internal flow in channels of structurally complex bodies

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Annotation. For the study of turbulent configurations in complex channels, it is proposed to use the experimental method of mass entrainment in combination with theoretical analysis and mathematical description of the results obtained. The paper presents the results of numerous experiments conducted on high-enthalpy gas flows in nozzles of complex shape. Images were obtained that visualize the picture of the torsion-wave dynamic movement of gas flows, the presence of stable structured turbulent flow configurations, and the abrupt transition from one form of flow stability to another.

Introduction

We are surrounded by a great many types of flows of liquids and gases. The study of these trends is given a lot of attention in the literature [1]–[11]. All these types are conventionally placed in two large groups: "laminar flows", when each particle of the liquid moves parallel to the main direction of the flow, "turbulent flows", when the flow is represented by a combination of a huge number of vortices. All gas dynamics, flight theory, and hydrodynamics are ultimately just an attempt to understand the mechanics of the formation and interaction of flows with various bodies, surfaces, and channels, as well as to find methods of mathematical description and calculation of these processes. The issues of heat transfer in the areas of separation and re-joining of compressed gas flows are directly related to the dynamics of motion and are considered by many researchers [12].

The analysis of various types of turbulence in complex channels confirms the validity of the following statements: turbulence is a system of stable forms of flow; turbulence is a combination of four types of simple flows (translational, vibrational, rotational and torsion).

Three-dimensional flow of liquid, gas and plasma inside chambers, nozzles, air intakes and other flow paths of complex shapes, as a rule, is turbulent. In General, in any, even in the simplest channel, which has a high degree of symmetry, the flow can be quite complex and depend largely on the mode that determines the combination of independent types of flow [13]. The presence of rotations, rotations, wall vibrations and the combined effect of these factors on the working body leads in addition to the complexity of the flow structure and the emergence of new stable forms, which include the classic Taylor-Getler pair vortices.

For flow paths we can conditionally distinguish three independent types of flows:

in axisymmetric channels;

in asymmetric channels;

in axisymmetric channels with asymmetric input conditions.

These types of currents can be combined. For example, rotated about the axis of the combustion chamber of an elliptic supersonic nozzle with an oblique cut combines axisymmetrical current along the cylindrical chamber, the rotation in the supersonic part of the nozzle, the flow inside the nozzle with an elliptical orifice and flowing through a slanting cut with POS-now, the next sharp bend of the stream. Similar flows are those in turbines and LRE pumps, where the process is complicated by the additional rotating movement of the channel walls.

Complex forms of channels lead to the formation of various vortex structures of moving flows. Combinations of these three types of currents give rise to secondary, tertiary and multi-branched flows. In their mathematical description, we have to deal with increasingly complex ways of setting boundary conditions that adequately describe the flow.

Many flows in complex channels cannot be predicted analytically or computationally at present. An experimental approach is used to describe them. One of the effective experimental methods for observing traces of complex turbulent flow near the walls of various structures is the method of mass entrainment or the method of hot visualization. This method is used for research of high-enthalpy flows, such as the flow in the flow paths of solid- fuel rocket engine, the movement of descent vehicles in the atmosphere, as well as processes occurring in the designs of nuclear power propulsion systems.

Experimental methods, unfortunately, also do not always allow you to get the desired result. It is difficult, for example, to measure the angular velocity of the steam flow in the turbine nozzle. It is almost impossible to measure the pressure at the junction of the electric arcs of a three-phase plasma torch. It is a big problem to measure the velocity profile of a uranium plasma fuel element in a gas-phase nuclear reactor. In such cases, experimental and computational methods are used to model flows in complex channels.

Method of the study of the flow structure and installation

For the study of turbulent configurations in complex channels, it is proposed to use the experimental method of mass entrainment in combination with theoretical analysis and mathematical description of the results obtained.

The essence of the method is to organize the conditions under which a high-enthalpy gas flow leaves a trace on the investigated carried-away surface. At the same time, polymer materials that obey the laws of linear pyrolysis are used as the carried-away material, when the rate of destruction and entrainment of the material is almost directly proportional to the heat flow. Preliminary experiments are conducted for various materials with these properties: fluoroplast 4, polymethylmethocrillate, viniplast, as well as some fiberglass and graphite. The work done shows that fluoroplast-4 is the most suitable material for the created installation, the selected time and temperature conditions of the experiment.

An important aspect of research is the short duration of the process. The correct selection of the peak time provides a clear "instantaneous fixation" of the three-dimensional structure, eliminates the imposition of one gas-dynamic pattern on another, and also eliminates the influence of the formed traces in the material on the subsequent flow structure.

For experimental research, a model installation [14] was developed, which is a small-sized solid-fuel rocket engine (sfr) (Fig.1). It consists of a combustion chamber and a nozzle block. The chamber contains a solid fuel charge and a fuse. The dimensions of the charge and its shape are determined in advance to set the desired pressure and the burning time (exposure time to the sample). The nozzle is made collapsible and has a glass in which a fluoroplastic sample is laid, simulating a full-scale nozzle or channel. The liner of the critical section of the nozzle is made of a carbon composite material with a low entrainment rate compared to the fluoroplastic of the test sample. The described design allows you to explore a variety of configurations of channels and nozzles, repeatedly on one working part to produce launches of high-enthalpy flow. Left after exposure to hot gas prints make it possible to visualize the relief structures of the flow near the washed walls. Measurements of the geometry of the resulting patterns allow you to build profiles of entrainment along the generators.

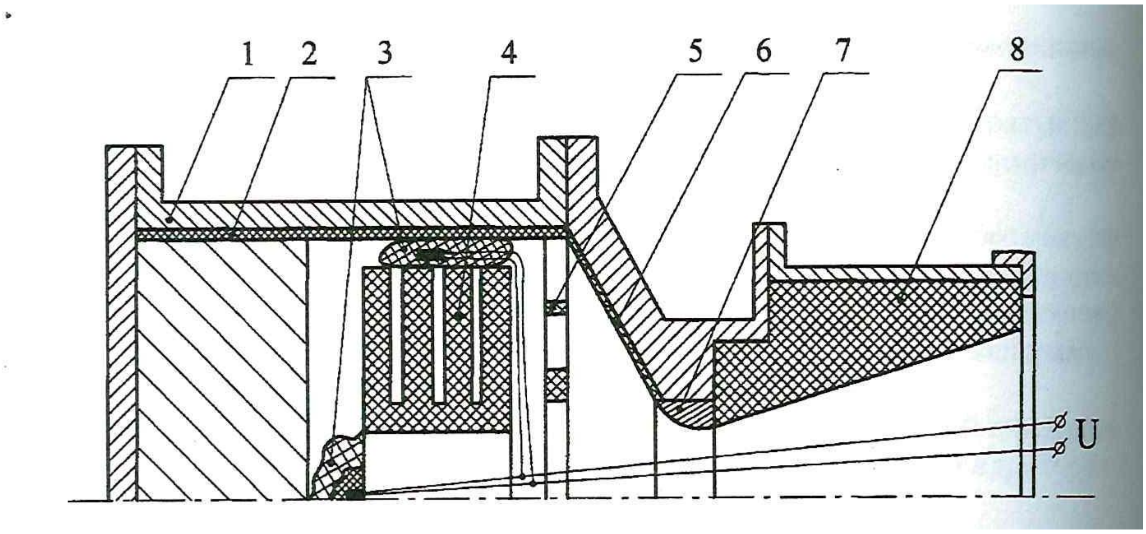

Figure 1. The scheme is a model SFR for the study of turbulent flow configurations.
1 — case; 2—heat-protective coating; 3—igniter; 4—charge; 5—diaphragm; 6—cone;
7—liner; 8—test sample of fluoroplast.

The results and generalization of numerous experiments conducted on the described installation on the study of the physics of turbulent flows in the channels of structurally complex bodies are given below. the gas flow Velocities vary from zero at the wall to supersonic in the core.

Results and discussion

1. Flow in an axisymmetric conical nozzle

Let's start by describing the flow structure in an axisymmetric conical nozzle. Research is carried out on the described model solid-fuel installation with a nozzle made of fluoroplast. Nozzles with different angles of opening of the supersonic part are tested. Experiments are carried out using different compositions of solid fuel, at different pressures in the combustion chamber and different percentages of condensed combustion products (mass fraction of condensate from 0 to 0.4). As a result of research, it was found that the peak in the supercritical region occurs in a stable gas-dynamic mode. At the point of transition from the non-combustible liner of the critical section to the inflaming fluoroplastic cone, a so-called "supercritical pit" occurs, in which a zone of subsonic flow is formed with the formation of Taylor-Gertler vortices. The vortex structure can be visualized by carrying away the mass of the fluoroplastic nozzle. In time, this structure (Fig.2) does not change, the number of vortices is preserved, and their size increases in proportion to the time of acceleration. It is established that the amplitude of the vortices $\Delta\delta$ obeys the empirical ratio $\Delta\delta/\delta max=0{,}2\ Go^{-0{,}2}$ and, as can be seen, depends on the Gertler number Go.

The amplitude of the vortices is also functionally related to the maximum depth of the "pit". The experimental dependence of the maximum entrainment value δ_{max} obtained for cones with different slopes of the generators is uniquely determined by the angle of entry into the supersonic part of the nozzle θ_{in}: $\delta_{max} = S_{max}\ (0{,}525 — 0{,}25\ tg\theta_{in})$, S_{max} -the coordinate of the maximum entrainment point along the forming nozzle.

The absolute value of the magnitude of the amplitude $\Delta\delta$ is approximately 10 % of the value δ_{max}. At sufficiently strong peaks downstream, cellular formations are visualized, evenly spaced around the circle in a staggered order. These are traces of torsion of the stream.

Photos of prints (Fig.2) shows that even in non-stationary processes, turbulent structures are not chaotic, but strictly ordered. The vortex structure of the flow is stable, once born, the prints of the vortex bundles are repeated in the next experiment on the same sample placed in the installation after measurement.

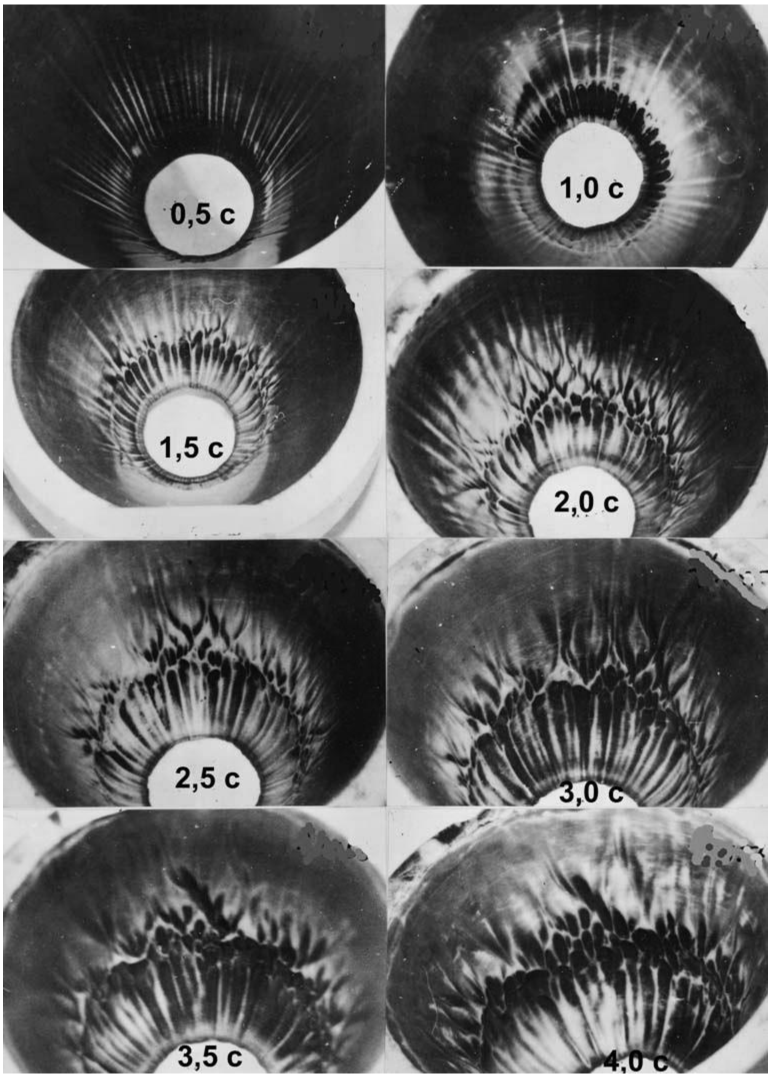

Figure 2. The imprint of the Taylor vortices of Getler in the area of the height of the conical nozzle

The resulting photo also demonstrates that after passing the "supercritical pit" the flow becomes laminar.

2. Turbulence in the prismatic nozzle

A prismatic or rectangular nozzle has either a rectangle or a square in its cross section. In this case, the angle of inclination of one pair of opposite planes is zero. If the height of the rectangle is much less than the width, the nozzle degenerates into a flat slit.

The peculiarity of the flow in a prismatic nozzle is that the expansion of the flow along adjacent planes is different and greater where the angle of their inclination to the axis is greater. This would lead to axial currents. But since there is no turbulence in the supersonic flow, a spatial system of jumps is formed in such a nozzle. Near the walls, at the height of the nozzle, subsonic zones are formed. Local pressures in these zones correspond to the degrees of expansion along each of the forming planes, where the corresponding axial flows are formed.

Experiments carried out on prismatic nozzles made of fluoroplast show that Taylor-Gertler vortices are formed on the faces of prisms. The values of the amplitudes of these vortices are inversely proportional to the values of the angles of inclination of the planes and obey the dependencies for the

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conical nozzle. In accordance with these dependences, the vortex amplitudes of the studied nozzles differ from each other by about 20 %.

At the intersection of the planes, on the edges of the prism, a larger single vortex is formed, the size of 2.5-3 times larger than any of the vortices on the faces of the nozzle (Fig.3). It is obvious that the parity of this vortex is provided by vortex flows in the core of the flow at some distance from the wall.

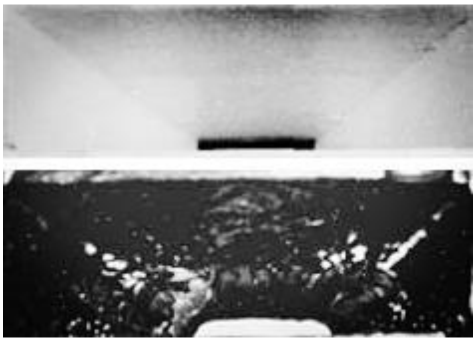

Figure 3. The imprint of the vortex flow in the zone of the height of the prismatic nozzle

3. Turbulent flow in elliptical nozzles

A similar flow is obtained in experiments on an elliptical nozzle. Unlike a prismatic nozzle, there is no angular vortex on an elliptical nozzle. In this case, the size of the Taylor-Gertler vortices change inversely proportional to the angle of inclination of the generators. They are larger along the minor axis of the ellipse and smaller along the major axis (Fig.4). Analysis of flared nozzles allows us to establish the unevenness of cellular prints located downstream of the longitudinal vortices. Along the generatrix, which lies in the plane of the small axes, the cells of the imprint are larger, and the large ones are smaller. The cells are staggered with a half-period shift. These are prints of oppositely rotating paired bundles formed as a result of torsion of the stream. The analysis shows that the torsion region of the flow is located at the zero pressure gradient.

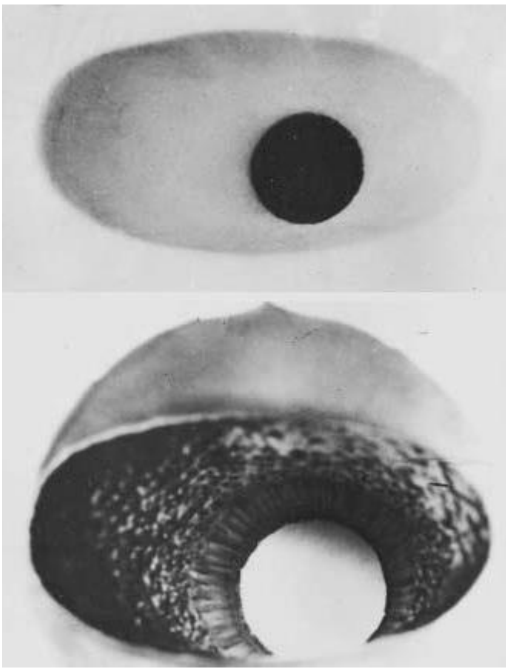

Figure 4. The imprint of the vortex flow in the zone of the height of the elliptical nozzle

IOP Conf. Series: Materials Science and Engineering **779** (2020) 012030 doi:10.1088/1757-899X/779/1/012030

4. Analysis of turbulent flows in a segment nozzle

Segment nozzles are used to remove the exhaust jets of auxiliary engines from the surfaces of the bodies and critical components of the rocket. Typically, these are conical nozzles with a flat section parallel to the axis of the camera. In the area where the nozzle is "cut off" the flow is deflected relative to the conical wall.

Experiments show (Fig.5) that areas of Taylor-Gertler turbulence additionally occur behind the fracture site on the plane. The intensity of the vortices is directly proportional to the difference between the angles of the forming cone and the slope of the cut plane. Vortices in this case arise after the flow of a complex turbulent secondary flow formed by a "supercritical pit" in the undeformed segment of the nozzle. The new vortex flow formed behind the fracture is tertiary, since it is obtained by the complication of the previous secondary one. But as you can see in the photo, this new current is as orderly as the secondary one. It is a vortex, and the size of the Taylor-Gertler vortices is comparable to the size of the secondary flow vortices.

In the area of the interface of the conical surface and the cut plane, single larger vortices are observed. Their nature is similar to the vortices in the edges of the prismatic nozzle.

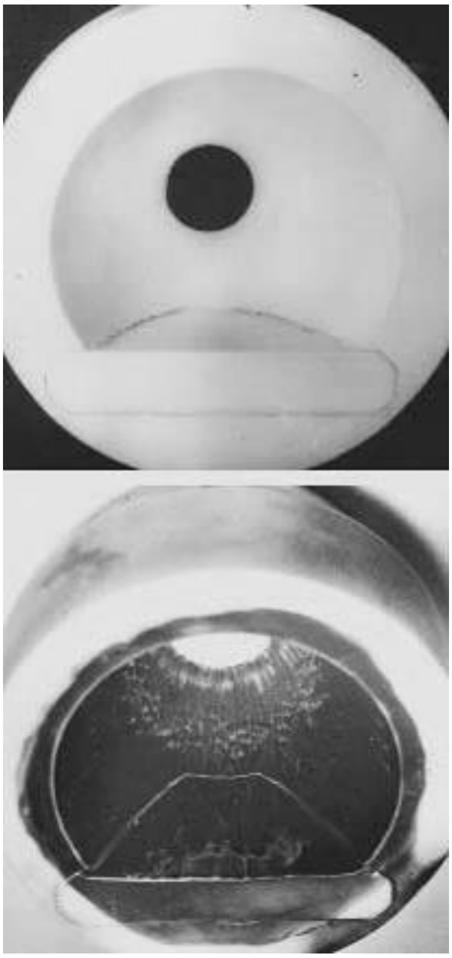

Figure 5. The imprint of the vortex flow in the zone of the peak of the segment nozzle

5. Current in the oblique nozzle

The oblique nozzle is used to sharply rotate the supersonic flow at an angle of up to 30-40° relative to the axis of the combustion chamber and create a constant control lateral force. Experiments carried out by the method of mass entrainment on conical nozzles with an oblique section show (Fig.6) that the presence of an oblique cut does not have any effect on the turbulent structure of the previous supersonic flow. All forms of flow stability at the wall do not undergo any changes during the transition to the short, long and middle forms. In this case, the characteristic property of all supersonic flows is manifested, when there is no feedback up the flow, and the flow does not react to approaching obstacles and changes in the shape of the nozzle wall.

The presence of an oblique cut does not lead to positive pressure gradients if the longest part of the wall is operating in the design mode. If it operates in the mode of overexposure, then in this area there are local secondary spatial flows directed into the nozzle.

Figure 6. The imprint of the vortex flow in the zone of the height of the conical nozzle with an oblique section

6. The rotary control nozzle (RCN)

The turbulent flow in the rotary control nozzle depends significantly on the conditions at the entrance to the supersonic part, and depending on these conditions, as well as on the length and shape of the supersonic nozzle, the flow structure is formed on the windward and leeward part. The trivial rotation of the nozzle relative to the combustion chamber can not serve as a criterion for the appearance of the windward side in the area of the greatest geometric angle of attack. Along the wall of the nozzle there is a redistribution of pressure, which has an oscillatory character. Depending on the flow conditions, windward and leeward zones may be located successively on the same formation. In this case, the resulting lateral forces periodically change the sign. With a certain period, the heat flows change, leading to asymmetric entrainment. The gas-dynamic structure of a two-phase turbulent flow also changes and becomes asymmetric. For figure 7 shows a photo of asymmetric entrainment due to condensed phase deposition. On the windward side, there is a trace of asymmetric burnout of the nozzle wall.

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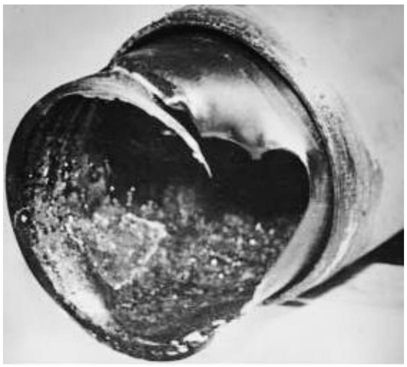

Figure 7. Burnout of the wall of the rotary control nozzle

7. Split control nozzle (SCN)

The split control nozzle differs from the rotary control nozzle in that the rotation of the flow is carried out in the supersonic part of it. Under the influence of steering machines, part of the nozzle is introduced into the stream, and part of it comes out, forming zones of windward and leeward currents, forming the resulting plot of pressure forces and lateral force.

For figure 8 traces of the influence of turbulent flow on the windward side of the SCN were recorded. The positive pressure gradient that occurs when the wall is rotated in the direction of the flow leads to the formation of Taylor-Gertler vortices. A similar picture is obtained on the segment nozzle. Tertiary currents are formed. But contrary to the expectation of a more complex flow pattern, when a highly turbulized flow at the wall runs into a wedge-like fracture and breaks in the area of impact against it, its structure on the contrary is simplified and becomes similar to the structure of the secondary flow. The sizes of Taylor-Gertler vortices still satisfy the dependences for the amplitude $\Delta\delta$, and their shape and number do not change over time.

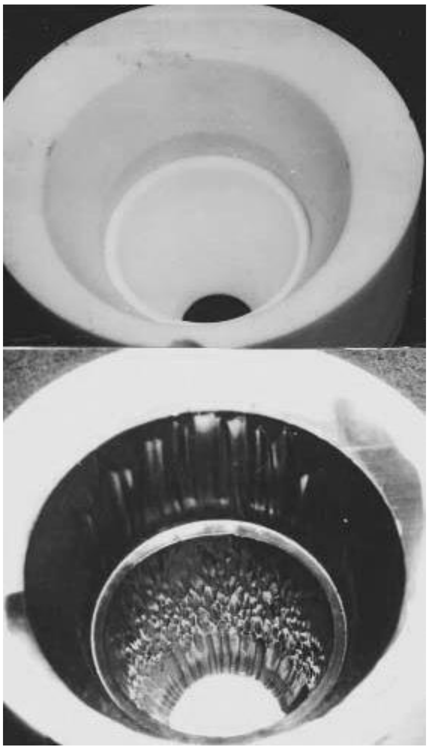

Figure 8. The imprint of the vortex flow in the zone of the height of the split control nozzle

8. Torsion structures in the high-altitude nozzle diffuser

When testing the high-altitude nozzle model LRE in the diffuser were recorded traces of three-dimensional flow on the wall, manifested in the form of prints of condensed combustion products of carbon-containing fuel (soot).

For figure 9 visible cellular formations on the surface of the diffuser, located in a staggered order with a shift of half a period. These formations occur as a result of contact of pairs of twisted bundles with the wall of the nozzle. This torsion flow is formed after the Taylor-Gertler longitudinal vortices flow into the gradient-free region. In this case, pairs of neighboring vortices form stable bundles (twists), lined on the surface of the wall.

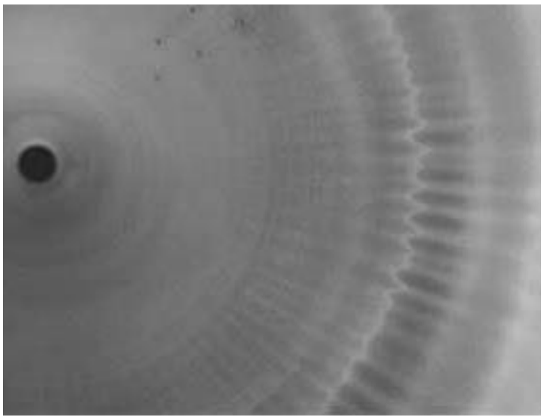

Figure 9. The imprint of the vortex flow on the surface of the LRE(liquid rocket engine) diffuser

Summary

The above examples of turbulent flow in channels of complex shape are the most significant. They clearly demonstrate the main provisions of the torsion-wave theory and confirm the fundamental statements.

1. Turbulence is a complex torsion-wave dynamics that reflects stable forms of highly structured flow of the working body in the channels and in the flow of complex aerodynamic forms. The transition from one form of stability to another occurs abruptly.
2. Any turbulent flow can be represented as a complex combination of four types of simple flows: translational, vibrational, rotational and torsion.

Maximum turbulence is realized at critical values of the flow, when its speed becomes equal to the speed of sound and almost equal to the speed of thermal (chaotic) motion of molecules. In criticism, the current jumps from turbulent to laminar. Channels of complex shape create conditions for the separation of the flow and the formation of vortex subsonic structures. Turbulence is impossible in a supersonic stream. Conditionally, it is triggered in the jumps of compaction, where there is a transition through the sound.

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