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FLOW STRUCTURE IN A FLAT VORTEX CHAMBER

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We investigate a flow in a flat vortex chamber in which the distance between the end walls is smaller than the radius of the chamber. The study was mainly performed by optical methods: a Töpler device was employed, with the Foucault knife replaced by a diaphragm. It is shown that the flow in the chamber has a complicated spatial structure. In addition to the basic helical flow, an intense "transverse" rotation of the type of Taylor–Görtler vortices occurs. In contrast to previously studied flows, where these vortices were observed near a concave surface, in the motion considered transverse vortices occur in the entire working volume of the chamber. In this case, four parallel vortex filaments are formed. The high intensity of the vortices has allowed one to visualize them by the Töpler method and by "tinting" the flow by highly disperse particles. Quantitative dependences of the dimensions of the vortex cells on the flow regime, i.e., on the pressure of gas deceleration, were obtained.

Regularities of the motion of a gas that is tangentially injected into a flat chamber with a central inlet were studied experimentally and theoretically in [1–6]. In these studies, a certain "averaged" motion is considered that can presumably be represented as a potential vortex with a certain vortex constituent beyond the boundary layers and the regions adjacent to the inlet and outlet channels.

In this paper, we give results of a detailed study of the indicated motions in a chamber with central and tangential outlets. The flows considered are shown to have a complicated structure, and it is shown that the main vortex is superimposed by transverse vortices of the Taylor–Görtler type [3–5].

To study the motion of a gas and solid particles, we created a stand (Fig. 1) that includes a cylindrical vortex chamber 1 ($h^0 = h/R = 0.45$, where h is the height of the cylinder and R is its radius) with transparent end walls, a complex of optical equipment 2–4, meters of acoustic signals 5, oscillographs, spectral analyzers 6, a PC, a pneumatic system, an illuminating system, and a system of power supply. The flow studies were carried out in working chambers of different dimensions ($R \leqslant 125$ mm), but all the chambers were geometrically similar. In the process of operation of the device, compressed air was fed into the chamber through a contracting nozzle 7 of rectangular transverse cross section ($S_{\rm in}^0 = S_{\rm in}/S_0 = 0.013$, where $S_{\rm in}$ is the area of the inlet nozzle and $S_0 = \pi R^2$ is the cross-sectional area of the chamber) along the tangent to the generatrix of the inner cylindrical surface, i.e., the gas is fed tangentially. There is a circular contoured hole 8 in the middle of the chamber in one of its end walls ($S_c^0 = S_c/S_0 = 0.05$, where S_c is the area of the central hole) that connects the internal volume of the chamber with the atmosphere. In addition to the central hole, there is a deflecting nozzle 9 that is shifted relative to the inlet nozzle by 90° streamwise (Fig. 1) and whose geometry and method of connection to the chamber are similar to the inlet nozzle. As trials showed, the gas flow rate through the central nozzle is approximately half that through the deflecting nozzle, which plays a certain role in flow stabilization and partially compensates the perturbing influence of the inlet nozzle on the flow in the chamber. Gas with preset parameters, which are varied in the process of investigation, is fed into the chamber by the pneumatic system.

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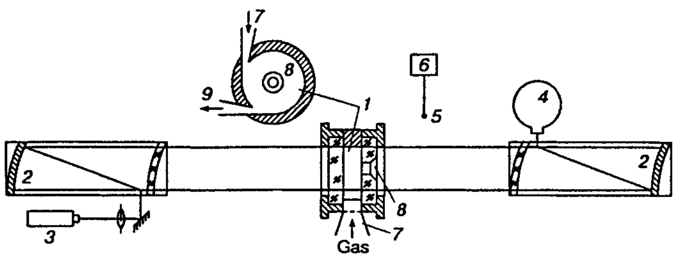

Fig. 1

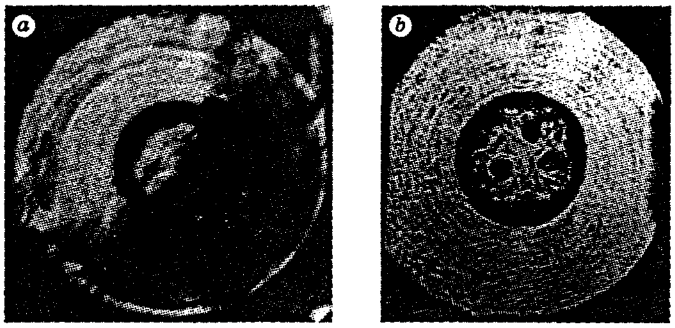

Fig. 2

The optical system of the stand consists of an IAB-451 Töpler device 2 and light sources 3 (an ILGI-101 powerful laser, a spark discharger, a mercury lamp, and a flash tube). The laser generates light pulses of duration 40 nsec with a frequency of 10 kHz, and the spark discharger and the flash tube generate single pulses of duration 1.5 and 300 μsec, respectively. The development of the motions considered was visualized and recorded as Töplerograms with the use of the optical system and a ZhLV-2 time magnifier 2 (up to $8 \cdot 10^6$ frames/sec).

To determine the level of acoustic signals, we used gauges (capacitor microphones), amplifiers, and analog converters that were produced by Bruel and Kjer, as well as piezoelectric transducers.

A frequency analysis of the signals was performed, and the results and the signals themselves were introduced into the PC memory, together with readings of the remaining devices, in particular, the meters of static and full pressures in the flow.

In some experiments, the Foucault knife in the IAB-451 device was replaced by a circular diaphragm, which made it possible to visualize periodic structures associated with high density gradients in the entire axisymmetric flow. Figure 2b shows a Töplerogram frame of the flow in the chamber that was obtained in the indicated way. The exposure time for a frame was 40 nsec, and the light source was an ILGI-101 laser. The concentric light and dark rings on the frame correspond to concentric zones of sharp density gradients.

Figure 2a shows a Töplerogram frame that was recorded in the standard operational mode of the IAB-451 with the use of a Foucault knife. The light source here was an ISSh-400 flash tube. The visualization conditions for a flow in a narrow sector of the chamber, with a chord perpendicular to the Foucault knife edge, are similar to those in the chamber sector with the use of a round diaphragm, which offers the possibility of determining the flow structure in the indicated sector by means of this visualization technique as well. Indeed, as is seen in Fig. 2, the flow patterns mainly coincide. The lower degree of contrast of Fig. 2a is explained by a significantly longer exposure time of a frame in this case.

As trials show, the distance between the dark and light bands δ does not depend on the wavelength of the illumination source, but it is determined by the flow regime in the chamber (for example, this distance depends on the pressure of gas deceleration in the chamber P_0). The density in the Töplerogram frames remains constant in time. The structure of the density gradients thus determined can be interpreted as a system of

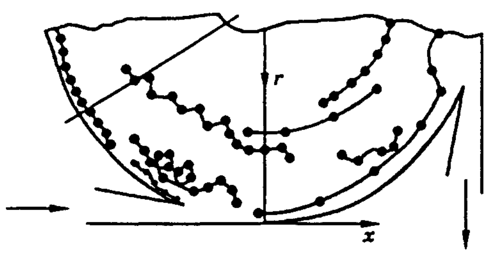

Fig. 3

Fig. 4

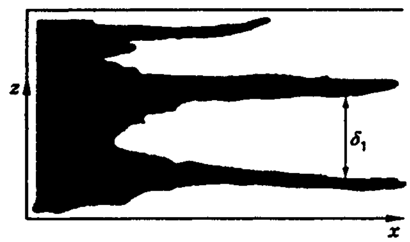

Fig. 5

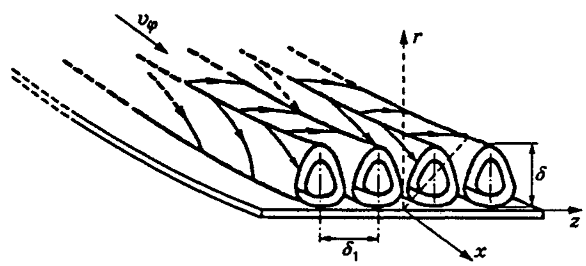

Fig. 6

inertial waves with a zero phase frequency, since the values of the density gradients are almost stationary. However, the authors consider this structure to be associated with transverse vortices superimposed on the main flow in the chamber.

The vortex nature of the ring-shaped zones is confirmed by the film recorders of the motion of fine particles in the working chamber. Disintegrating after an impact against a lateral surface, the coarse particles that were introduced into the chamber produce fine but distinguishable particles of diameter 0.2–0.5 mm, which "tint" the gas volumes associated with these particles. Thus, the possibility of tracing the motion of separate elementary gas volumes arises.

Figure 3 gives examples of trajectories of such particles that were constructed based on film records (the projection onto the plane of the cross-sectional area of the chamber is shown). The points on the trajectory curves indicate the moments of exposure of a successive frame. The time interval between the frames was 100 μsec. The presence of the trajectories, which are similar to cycloids (projections of a helical curve), indicates the existence of transverse vortices in a rotating flow. The density gradients, which are associated with the transverse motion of the gas, allow one to visualize the flow (see Fig. 2) and to establish the positions of these vortices.

The rotation frequency of the medium inside transverse vortices can be approximately found using time marks on the trajectories. In the experiments considered, we have f = 3–5 kHz (two cycloidal curves in Fig. 3). The mean linear velocity of particle motion along a circumference of radius $r \sim 60$ mm is $v \sim$ 45–240 m/sec, and along a circumference of radius $r \sim$ 35–40 mm it is $v \sim$ 60–180 m/sec.

We determined the fine flow structure in the direction orthogonal to the plane of the end walls (in the plane of the rings shown in Fig. 2) and in the boundary layer at the chamber end surfaces (Fig. 4) by introducing highly disperse particles of nicotinic resin. The resin particles stick to the lateral surface of the chamber nonuniformly because of the presence of transverse vortices in the flow. These particles deposit more intensely on the lateral chamber wall compared with the region in which the "transverse" velocity of the vortex flow is maximum, which causes detachment of the resin particles.

The experiment showed that there are four such cells in the chamber under study (two pairs of transverse vortices with counter motion). Indeed, as is seen in Fig. 5, where a picture of the content of

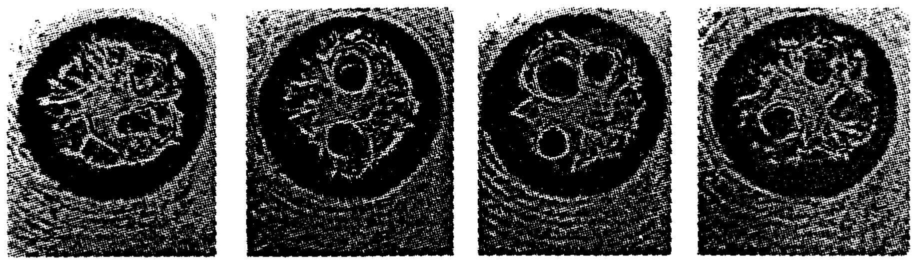

Fig. 7

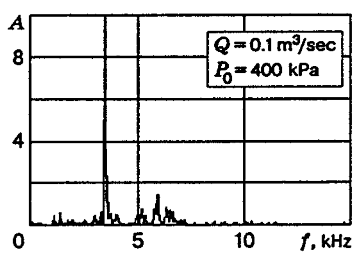

Fig. 8

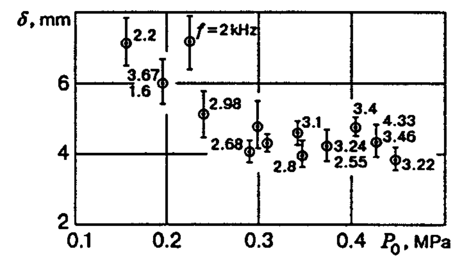

Fig. 9

highly disperse resin particles on the chamber lateral surface is given, there are three distinct lines of particle deposition, which correspond to four cells located between these lines and the side surfaces. The tracks drawn by the resin particles on the end surfaces (Fig. 4) are the classical Ekman spirals. The boundary layer here is an Ekman layer.

We analyze the results obtained. The flow comes to the chamber from a rectilinear rectangular channel. The gas velocity at the nozzle section is 200–300 m/sec (Re $\approx 3 \cdot 10^5$), i.e., a turbulent flow regime occurs. Interacting with the concave lateral wall, the flow decelerates. The gas velocity near the wall becomes lower than the velocity of the layers lying above. Owing to the action of the centrifugal force, the layers that are more distant from the wall but move with higher velocity displace the lower layers.

The negative pressure gradient that appears leads to the occurrence of instability of the main flow that is similar to the instability observed in a liquid between rotating concentric cylinders [4]. For example, in the case of bending of a flow in a bend, this leads to generation of "transverse" vortices (Görtler vortices [3]) in a liquid (gas) layer adjacent to a concave wall. The shape of these vortices is shown in Fig. 6 (taken from [5]). It is seen in Fig. 2 that in the situation that we consider, the transverse vortices occupy the entire volume of the chamber because of the helical character of the flow. The dimension of the cells in the direction of the radius is somewhat smaller than the corresponding dimension of the cross section of the inlet nozzle.

Figure 2 also shows the flow structure inside the central outlet; the gas flows from the working chamber into the atmosphere through an annular zone, the near-axial region being a negative-pressure zone at which vortex-free gas from the surroundings arrives continuously. Linear vortices circulate between the central and annular zones. The vortices are three in number in a steady-state regime. In reaching this regime or in changing regimes, two to five vortices arise (Fig. 7).

In concluding, we note some special features of the acoustic signals generated by the chamber. The spectrum of these signals can serve as an indicator of the occurrence and relative intensity of aerodynamic processes developed in the flow considered.

Figure 8 illustrates the spectrum of a generated signal. This spectrum has a line character. In frequency composition, the spectrum can be divided into four ranges: 200–700 Hz, 1.6–3.5 kHz, 6–12 kHz, and 25–40 kHz. Possibly, the first range is connected with volume resonating of the chamber, the second is related to self-sustained oscillations of the flow in the outlet nozzle (~2.5–2.7 kHz) and rotation of the medium in transverse vortices (~3 kHz), the third is associated with various modes of intrinsic gas oscillations in the chamber, and the fourth is connected with vortices that detached from the section of the outlet nozzle — the periodic character of the perturbations in this flow zone (the period is ~30 μsec) is revealed by means of Töplerograms.

We dwell upon acoustic oscillations in the range of ~3 kHz. A comparison of the frequencies of this range, which are fixed in the experiments, with the size of the vortex cells δ, is given in Fig. 9, where the dependence of δ and the values of the corresponding frequencies f on the deceleration pressure P_0 of the gas that is fed into the chamber is shown. Clearly, for a relatively low pressure ($P_0 < 0.3$ MPa), both parameters depend strongly on P_0 (for δ, the dependence is close to linear). Upon an increase in the pressure (for $P_0 > 0.3$ MPa), the size of the cells and the values of the corresponding frequencies stabilize. The flow structure in the chamber stabilizes as well.

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