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Mechanical Effects in a Vortex Device with a Rotating Core

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Abstract—The process of the appearance of forced rotation of an axial core mounted in a modified vortex tube in the direction opposite to the rotation of the air vortex and the precession of its axis have been studied. It has been established that dynamical bending of a metal axial core arises in the process of rotation which causes mechanical wear of its end part and fracture in the fastening area of the bearing without residual curvature of the core axis. The excitation of rotation and observed force effects are not related to the mechanical action of rotating air flow on the axial core.

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Investigation of the vortex Ranque–Hilsch effect has been carried out in many theoretical and experimental studies and discussed in detail [1]. Until the present time, there has been no consolidated opinion on the physical essence of this phenomenon. In most papers, the mechanism for separating a swirling flow onto the cooled core and hot peripheral layers, as well as the thermogasdynamic parameters of devices that implement the vortex effect, are studied. The presence of three-dimensional structures with a screw form in swirled flows and the significant effect of precession of the vortex core on the process of energy separation have been established experimentally [2].

In addition to the effect of energy separation, mechanical effects are observed in vortex devices that are not clearly explained. In [3], the effect of rotation of a metal axis introduced into the vortex cooler in the direction opposite to the rotation of the air vortex with a rotation frequency of about 50 Hz was observed. In [4], it was shown that cylindrical objects rotating in opposite directions execute precessional motion in the direction coinciding with the direction of the flow and the rotation frequency depends on the pressure at the inlet. It was found that tangential components of rotation velocities of the peripheral and axial vortices in a vortex tube are directed in one direction [1]; i.e., they do not change the direction of rotation.

For experimental investigation of the above effect, a vortex device on the basis of a counterflow vortex tube was used. The schematic diagram of it is shown in the figure.

Inside of expansion chamber *1* of the vortex tube, axial metal core *2* was mounted, which was free to rotate on two rolling bearings. The length of the cantilever part of the core inside the vortex tube is 87 mm. Through elastic bushing *3*, the core is connected to disk *4* rotating on a ball bearing. Bushing *3* was used to minimize vibrations of measuring disk *4* during operation of the vortex device. On disk *4*, a reflective strip was placed to measure the rotational speed of the axial core using a Mastech MS6208B noncontact (laser) digital tachometer. The inlet of the vortex tube has the form of a "snail," and the thickness of snail *5* is 2.5 mm. The inner diameter of the expansion chamber of the vortex tube is 10 mm, and the length is 76 mm.

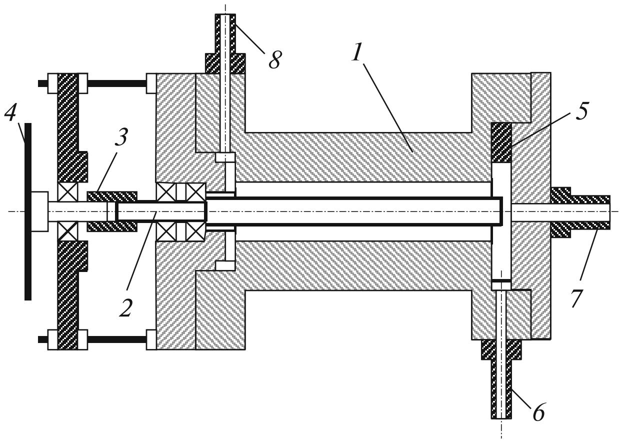
Pressure $P_I = 0.1$–0.6 MPa was fed from the compressed-air network onto inlet connection *6* of the vortex tube (see figure). The temperatures of the cooled and heated air leaving the vortex tube were measured using two Mastech MY64 multimeters, the ends of the standard thermocouples of which were installed inside rubber tubes fitted onto chilled-air connection *7* and connection *8* of heated air.

In the experiments, we used metal axial cores of 4.0, 5.0, and 6.0 mm in diameter made of smooth calibrated low-carbon steel rods.

The experiments showed that, when setting an axial core with a diameter of 6 mm at air pressure $P_I \sim 0.1$ MPa at the inlet, an unstable (proceeding in jerks) forced rotation of the core was observed in the direction opposite to the rotation of the air vortex formed by the snail inlet.

With increasing air pressure at the inlet of the vortex device up to $P_I = 0.6$ MPa, the rotation frequency of an axial core increased up to 100–150 Hz in the direction opposite to the air-vortex direction of rotation.

When mounting the cores with diameters of 5 and 4 mm, the rotational frequency was lower. The maximum rotation frequency at $P_I = 0.6$ MPa reached the values of order 65 and 50 Hz, respectively, and unsta-



Schematic diagram of the vortex device.

ble forced rotation of the core started only at air pressure $P_I = 0.12–0.15$ MPa.

The used design of the vortex structure with a snail inlet made it possible to set both right- and left-handed screw rotation of the vortex due to overturning or replacing the snail. The conducted experiments showed that, in both cases, the forced rotation of an axial metal rod occurs in the direction opposite to the rotation of the air vortex. Thus, we confirmed experimentally the presence of a previously noted effect of rotation of a metal axis installed in the vortex device in the direction opposite to the direction of air-vortex rotation [3, 4].

In this case, if axial outlet of cooled air *7* (see figure) in the process of vortex-tube operation was shut, then the rotation frequency of the core did not change. If outlet *8* of the heated air was shut (see figure), then the rotation frequency of the axial core reduced by up to 50% at vortex-tube inlet pressure $P_I = 0.25–0.3$ MPa and by 10–20% at pressure $P_I = 0.5–0.6$ MPa. This can be explained by a decrease in the length of the interaction zone of the vortex with an axial core. In addition, the direction of rotation of the core in both cases did not change, being opposite to the rotation of the air vortex.

The conducted experiments also showed that the forced rotation of cores gives rise to forces and torques leading to precession of the axis of the rod and its strong bending during rotation. This resulted in a mechanical contact between the end part of the core and the inner surface of the vortex-tube expansion chamber.

In experiments with a metal core 4 mm in diameter, the lateral clearance between the core and the surface of the vortex-tube expansion chamber was 3 mm. This eliminates the mechanical contact of the core between the surface of the expansion chamber under its elastic bending and a gap in the bearings. However, as was showed by the experiments, a metal core with cantilever mounting on two ball bearings is sharpened on the cone due to friction about the inner surface of the vortex-tube expansion chamber during its forced rotation within a few minutes. The length of the formed conical part was about 15 mm at a length of the cantilever part of 87 mm. As a result, the core diameter at its end is 3.3 mm at an initial diameter of 4.0 mm. When using axial cores with diameters of 5 and 6 mm, their forced rotation led to the formation of a “brilliant belt” of 12–13 mm in length at the free end. This kind of mechanical wear of the end part of the axial core is possible only when touching the chamber walls, accompanied by S-shape bending and precession of the core axis during its forced rotation.

In this case, residual deformation (curving) of the core axes was not observed, since the axes of the cores remained straight after rotation stopped. This indicates that, during the forced rotation of the core, a significant dynamic bending occurred that is not associated with plastic deformation of the material.

Phenomena similar to the precession of the axis of an axial core in vortex tubes—flow pulsations (such as precession)—were experimentally observed in [2]. The precession of a vortex core in a Ranque–Hilsch vortex tube and precession of the core axis in the used vortex device have, obviously, the same physical nature.

The direction of precessional rotation of the vortex core observed in visualization of flows in vortex tubes coincides with the direction of rotation of the vortex itself. This gives grounds to suppose that, in the experiments described above, mechanical wear of the end of the core occurred when the direction of rotation of the core around its axis and the direction of axis precession were opposite.

Forces and torques arising in the process of forced rotation and precession of the axis of a core repeatedly led to breakage of cores with a diameter of 5 and 6 mm without curving their axes. Fracture of the core occurred in the stepped transition zone of the core to the shank for bearing a mounting with a diameter of 4.0 mm, despite preliminary processing of the transition zone to remove stress concentrators. The fracture of the core had the form characteristic for low-cycle fatigue at torsional bending—multiple foci of initial destruction in a thin surface layer and a fault zone in the central part with a granular surface. This means that, in the process of forced rotation, an axial core underwent strong cyclic bending at stresses in the material close to the yield point.

As measurements showed, when the vortex device operates with a mounted axial core, the Ranque–Hilsch effect of separation of the heated and cooled flows is practically not observed. With increasing pressure at the inlet of the vortex device, a slight cooling of air at both inlets *7* and *8* takes place (see figure). At $P_I = 0.6$ MPa, the temperature drop was 2–3°C relative to the air temperature at the inlet. This is obviously due to the usual flow throttling. When removing the axial core, the device worked like a conventional vortex tube. At air temperature at the inlet to the vortex tube $T_I = +24°\mathrm{C}$ and $P_I = 0.6$ MPa, the temperatures of the cooled and heated air were, respectively, $T_C = -13°\mathrm{C}$ and $T_H = +37°\mathrm{C}$.

We studied the effect of forced rotation and braking of an axial core on the air temperature at the outlet. The air temperature at outlets *7* and *8* of the vortex device was initially measured with a mechanically stopped core. Later on, the temperature at outlets *7* and *8* was measured in the regime of forced rotation of an axial core. It is established that the transition to the forced rotation of axial core leads to a decrease in the air temperature at outlet *7* by 2°C–3.5°C and a reduction of air temperature by 1°C–1.5°C at outlet *8*. A decrease in the temperature of outflowing air at both outlets may signify that the energy of the air vortex is spent on forced rotation of the core, despite the fact that they have opposite directions of rotation.

In [5], it was suggested that the counter-rotation effect of an axial rod noted in [3, 4] is due to a change in sign of internal twisting stresses (torque medium) near the axis of a vortex tube, but an explanation for this was not given. In the conducted experiments, the air rotates in a small gap (2–3 mm) between the core and the wall of the chamber of vortex tube. The direction of rotation is set by the "snail," and it cannot vary. Experimental results indicate that the forced rotation of an axial core is not due to the mechanical effect of rotating air flow on the axial core, as it is opposite to the direction of vortex rotation. The bending and twisting torques acting on the axial core during forced rotation leading to core failure and "sharpening" of its end part and cannot be explained by the action of the vortex flow on the core.

The effect that has been established may explain strong twisting and bending of objects in vortex processes, for example, in a tornado, which cannot be caused by simple kinetic pressure produced by a high-speed air flow.

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