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EXPERIMENTAL DETERMINATION AND ANALYTICAL INVESTIGATION OF CERTAIN PROPERTIES OF A FREE VORTEX

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The scheme of an experiment and certain results of the interaction of a free air vortex tube with a surface are considered. A solution of a differential equation for a plane cross section of a quasisolid tubular vortex core whose density varies according to a polytrope law is analyzed.

Real vortices obtained experimentally are usually considered as analogs of local atmospheric processes or as a form of flow in various power facilities [1, 2].

There are experimental facilities in which a free convective or a forced vortex tube is formed whose peripheral part does not touch any walls, but such vortices have a low rotational speed and power [3, 4].

In the present work we consider a technique employing pressure to create a free vortex tube whose power is limited only by the power of the blower and the heat source. This technique makes it possible to intensify substantially the processes occurring in free vortex tubes and to use their properties to create new facilities in the fields of power engineering, ecology, and transportation [5–7].

To create a gas (air) vortex tube, a flow in a short vortex chamber with tangential supply of the working body from a blower is used as the basic process. As is known [8], in this case at the outlet from the chamber an expanding rotating flow of conical form is formed at whose center a pressure close to atmospheric is established.

The vortex tube is formed due to compression of the conical flow subjected to the atmospheric (external) pressure appearing after the forced reduction of pressure at its center. The pressure is reduced with the aid of the same blower, and this results in the formation of the closed circulation loop of blower and vortex chamber.

The compression of the flow existing the vortex chamber increases its rotational speed in accordance with the law of conservation of angular momentum. Thus, the vortex tube is located in the surrounding medium at a distance from the bounding walls, between the suction pipe of the blower and any other surface. The latter requirement follows from Helmholtz's first theorem on vortices [9].

The setup for creating a vortex tube consists of a blade blower 1 that moves air along a closed loop consisting of an open vortex chamber 2 and a profiled cap 3. A solid or liquid (closing) surface 4 is located under the vortex chamber is (Fig. 1). Dashes show the vortex tube. The distances from the vortex chamber to the cap and the surface h_1 and h_2 may be varied within wide ranges, but the highest dynamic parameters of the vortex are observed at $h_1 = h_2 = 0$, which corresponds to the case of absence of mass losses to the surrounding medium. The setup made it possible to obtain a rotational speed of the air in the vortex of up to 70 m/sec..

The working portion of the setup for $h_1 = 0$ is shown in Fig. 2. At rotational speeds exceeding 10 m/sec a distinctive feature of the vortex tube is the presence of sharp boundaries between the tubular quasisolid region of rotation and the media inside and outside the tube. We noted an intensifying effect of heat supply to the surface 4, owing to which we recorded vortex tubes having lengths of several dozen diameters.

Vortex tubes with the rotation axis bent as much as 90° were observed at low rotational speeds. On some photographs small-sized spherical vortices were discovered that had a diameter about an order of magnitude smaller than the diameter of the vortex tube and were surrounded by two curved wakes.

When the lower end of the vortex tube interacted with a water surface of large extent, a bulge was formed on the free surface from which droplets detached and formed a fountain in proportion to the rotational speed of the air vortex.

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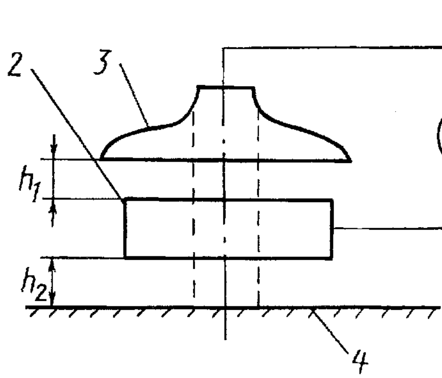

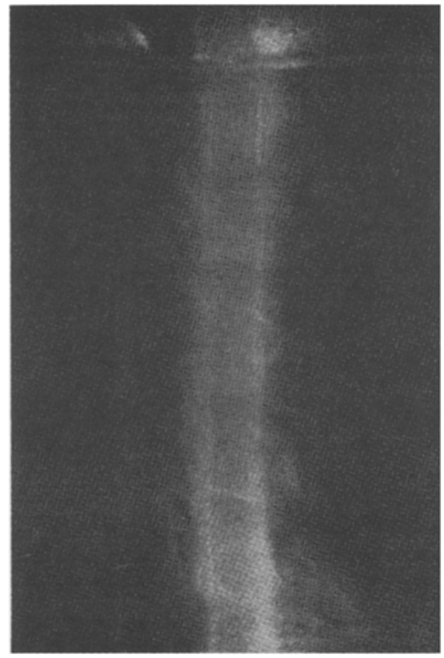

Fig. 1. Schematic of an experimental setup for obtaining an air vortex tube.

Fig. 2. Working portion of a setup with an air vortex tube visualized by smoke.

When the vortex tube interacted with a limited liquid surface (the free surface of water in a motionless vessel), a conical rough rotating water funnel formed in it. The process of rotation of the water was accompanied by its aeration.

An analysis of the capabilities of such a setup shows that the use of forced supply and suction of the working body to create a gas vortex tube at a distance from the walls permits one to obtain a rotational speed in the quasisolid core at comparatively small pressures that is very nearly equal to the theoretical limit.

Let us determine the basic properties of a free vortex tube that follow from the force balance equation for an annular plane quasisolid core, neglecting the effect of the transition zones within which the angular velocity of rotation of the particles is variable. To do this, we shall use a differential equation that was obtained in [10] under the same assumptions and that has the following form:

$$\frac{dp}{dr} + \frac{p}{r} = \rho\,\omega^2 r\,, \tag{1}$$

where r is the instantaneous radius of the plane annular quasisolid core.

Let us consider the case where the density of the working body obeys the equation for a polytropic curve p/ρ^n = const. Then, denoting the parameters of the external medium by the subscript "2," we obtain $\rho = p_2^{(n-1)/n} p^{1/n}/RT_2$, and Eq. (1) takes the form

$$\frac{dp}{dr} + \frac{p}{r} = cp^{1/n} r\,, \tag{2}$$

Here $c = p_2^{(n-1)/n}\omega^2/RT_2$.

Equation (2) is a Bernoulli differential equation, which has an analytical solution. By using the auxiliary quantity $z = p^{1-1/n}$ it can be reduced to the form $z' + ((n-1)/n)\cdot z/r = ((n-1)/n)cr$ with the general untegral

$$p\,(r) = \left[\frac{n-1}{3n-1}\,cr^2 + \frac{c_0}{r^{\frac{n-1}{n}}}\right]^{\frac{n}{n-1}}.$$

For the temperature distribution over the radius we obtain

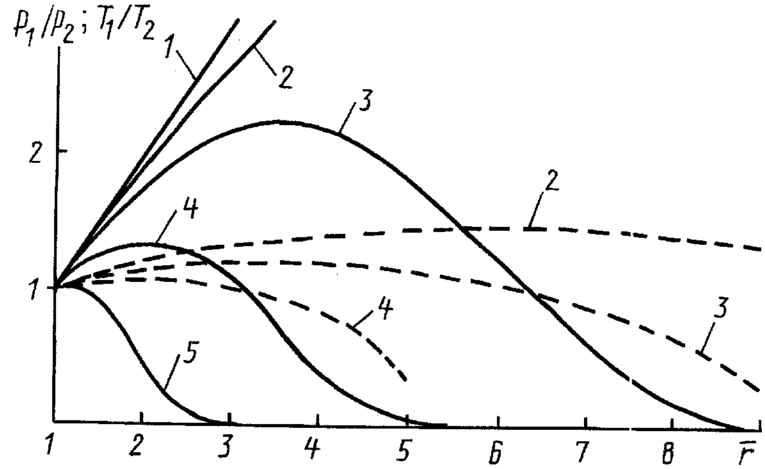

Fig. 3. Effect of the relative radius $\bar{r}$ of the core and the constant c_q on the ratios of pressures and absolute temperatures in a adiabatic air vortex tube (solid lines, ratio of pressures; dashed lines, ratio of temperatures): 1) c_q = 0; 2) $3\cdot10^{-3}$; 3) 0.01; 4) 0.03; 5) 0.1.

$$T(r) = T_2 p_2^{\frac{1-n}{n}} \left(\frac{n-1}{3n-1} cr^2 + \frac{c_0}{r^{\frac{n-1}{n}}} \right),$$

where c_0 is an arbitrary constant.

Assuming that $p = p_1$ and $T = T_1$ at $r = r_1$, we will find the ratios of the pressures and temperatures of the internal (with subscript 1) and external regions of the vortex. Then

$$\frac{p_1}{p_2} = \left[c_q \left(1 - \bar{r}^{\frac{3n-1}{n}} \right) + \bar{r}^{\frac{n-1}{n}} \right]^{\frac{n}{n-1}}, \tag{3}$$

$$\frac{T_1}{T_2} = c_q \left(1 - \bar{r}^{\frac{3n-1}{n}} \right) + \bar{r}^{\frac{n-1}{n}}, \tag{4}$$

where $\bar{r} = r_2/r_1$, is the relative radius of the vortex tube core; $c_q = ((n-1)/(3n-1))\cdot V_1^2/RT_2 = ((n-1) / (3n-1))\cdot V_2^2/\bar{r}^2 RT_2$ is the constant of the polytropic vortex.

The effect of the relative radius $\bar{r}$ and the constant c_q on the pressure and temperature ratios in an adiabatic vortex is shown in Fig. 3. From this figure it follows that there is the region with $p_1/p_2 \geq 1$ where spontaneous onset of a free vortex is impossible. In the setup considered the air vortex tube is formed by force, in particular, by reducing the pressure at the center of the flow exiting the vortex chamber. This scheme of operation of the setup makes it possible to decrease the predicted ratio of pressures to values $0 < p_1/p_2 < 1$, thus ensuring stable existence of the vortex tube. In this case the values of the constant c_q and the predicted ratio of pressures p_1/p_2 vary within wide limits that depend on the polytropic exponent and the relative radius $\bar{r}$.

The curves presented in Fig. 3 permit one to estimate the minimum rotational speed of a spontaneously existing atmospheric vortex. For $p_1/p_2 = 1$ and $1 < \bar{r} < 2$ this speed is close to the speed of sound. The largest calculated rotational speed of the core occurs in an isothermal vortex the pressure ratio in which is described by the equation [10]

$$\frac{p_1}{p_2} = \frac{\bar{r}}{\exp\left[c_T\left(1 - 1/\bar{r}^2\right)\right]}, \tag{5}$$

where $c_T = V^2/2RT_2$ is the constant of the isothermal vortex.

For an isothermal air vortex $c_T \approx 10$, while for an adiabatic one $(n = k)$ $c_q \approx 0.25$ (Fig. 3). Then $V_{max} = \sqrt{const \cdot RT_2}$. Assuming that $T_2 = 300$ K, we obtain $V_{max} \approx 1300$ m/sec for the isothermal vortex and $V_{max} \approx 500$ m/sec for the adiabatic one. It should be noted that the actual rotational speeds can differ from those predicted because of the effect of factors that were not taken into account.

CONCLUSIONS

1. The considered method for experimental formation of a free vortex tube makes it possible to substantially intensify its parameters and use various properties of it to create diverse technical facilities, in particular, in the fields of domestic appliances and power engineering, including transport facilities, etc.

2. It should be noted that compared to existing methods of producing vortex tubes it is possible to attain a higher efficiency for the process in the case considered due to the use of an annular scheme of motion of the working body and the absence of contact between the peripheral parts of the vortex and the wall.

3. The rotational speed in an isothermal vortex is higher than in an adiabatic one, which is possible only with heat supply that compensates the decrease in the internal energy due to the rotation and maintenance of the nonequilibrium structure of the vortex.

NOTATION

p, pressure; r, radius of a plane cross section; ρ, density of the medium; ω, angular velocity; n, polytropic exponent; R, specific gas constant; V, linear velocity.

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