CONVECTIVE HEAT AND MASS TRANSFER IN AN INSULATED TRAILING SWIRL (THEORY AND DESIGN OF VORTEX EQUIPMENT)

CONVECTIVE HEAT AND MASS TRANSFER IN AN INSULATED TRAILING SWIRL (THEORY AND DESIGN OF VORTEX EQUIPMENT)

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Abstract

The laws of convective heat-and-mass transfer in an insulated trailing swirl are experimentally and theoretically studied in this book. Based on experimental data on full-scale and laboratory vortices, the hydrodynamic structure of an insulated trailing swirl is found. The structure reflects the properties of both real hurricanes and flows in devices that operate using the principles of a vortex flow.

The author's hypothesis that turbulent stresses are proportional to the pair products of the components of the averaged velocity vector is used to create a common method of calculation of the laws of convective heat-and-mass transfer in vortex chambers, tubes, and elements of vortex apparatuses.

This book is intended for scientific workers and engineers working in the field of hydrodynamics, thermal physics, power, and chemical engineering and for post-graduate students and students.

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Foreword

Vortex flows find a wide application in various engineering devices. The basis for the engineering application of vortex flows is the field of centrifugal accelerations, whose values can be huge. Devices, where centrifugal forces are used, are separators, cyclone dust separators, driers, combustion chambers, vortex nuclear reactors, etc.

The domestic literature has many highly specialized books, where the heat-and-mass transfer of rotating flows are studied as applied to only one of the engineering devices. The level of presenting experimental and theoretical investigations in the books is different. In some books, the material is given on the basis of equations for ideal liquid, whereas in other books, on the basis of equations for viscous liquid in the Navier–Stokes form.

Therefore, no general laws of vortex flows, which are inherent in both atmospheric vortices and flows in apparatuses using centrifugal forces, are presented in the books dealing with the problem.

This book eliminates the disadvantages of the modern literature in the field of vortex flows and heat-and-mass transfer in them.

In Chapter 1, an analysis of experimental results on atmospheric vortices and vortex flows in engineering devices is used to form a hydrodynamic model of an insulated trailing swirl and to study the kinetics of a liquid particle in the vortex. The kinematic properties of the vortex allowed the author to describe laboratory models of an insulated trailing swirl. When describing experiments in laboratory models of vortex, the author comprehensively analyzes the errors of measurement caused by flow gradient and the errors in determining the center of vortex.

Usually, the errors are not discussed in the modern literature, whereas they are significant, as shown in this book.

One of the significant author's results is the detection of stable and unstable states both in laboratory and atmospheric vortices. This finding opens up the way to controlling vortex motions, which is important for designing optimum vortex apparatuses.

In Chapter 2, the general principles of turbulent motions are given. Here, the author presents a new hypothesis of closing equations of turbulent motion, which assumes that turbulent stresses are proportional to the pair products of the components of the vector of averaged motion velocity. Within the limits of the hypothesis, an analog of Bernoulli's integral in turbulent flows was obtained, and the basic properties of isoentropic flows were studied.

In Chapter 3, a convective heat transfer in an insulated trailing swirl is analyzed. Equations of the heat-and-mass transfer in a turbulent insulated trailing swirl are given in the context of the hypothesis. The equations are used to obtain the laws of interaction between the vortex line and the surrounding medium under the conditions of a self-simulating boundary-value problem.

The closed calculation scheme for the heat-and-mass transfer phenomena in an insulated trailing swirl, which is described in Chapter 4, is used for calculation of the main hydrodynamic and design parameters of vortex hydropneumatic apparatuses, such as a vortex chamber and tube, a centrifugal atomizer, and a vortex element.

This book contains original theoretical concepts of heat-and-mass transfer phenomena in a vortex, which are used to create reliable engineering calculation schemes for the hydrodynamic and design parameters of vortex hydropneumatic apparatuses.

Shashkov, A. G., Member of the National Academy of Sciences of Belarus

1

Experimentally Determined Properties of an Insulated Trailing Swirl (Single Vortex)

1.1 Atmospheric Vortex Formation

A few forces affect the motion of air in the atmosphere; the most important forces are pressure-gradient, Coriolis, centrifugal, and friction forces.

Pressure-gradient force is the main force that induces wind. If particles in the air were affected only by pressure-gradient force, the air should move along the gradient, i.e., from high pressure to low one. In actuality, the air moves in other directions because of the daily rotation of the Earth. Owing to the rotation of the Earth about its axis, the velocity vector of air flows in the atmosphere deviates from its original direction with reference to the coordinate system related to the Earth. This deviation is similar to that of the plane of the Foucault pendulum.

A pressure gradient leads to the formation of pressure maximums and minimums in the atmosphere, which make up a few hydrodynamic flows.

The Earth rotation continuously deviate all particles in the air that runs down from a baric maximum to all directions. Therefore, a giant vortex, where the pressure inside exceeds that in the surrounding medium at the same barometric height, forms around the baric maximum. Such a vortex is called anticyclone, and the rotation type of particles in the air, anticyclone rotation.

The flow around a pressure minimum is governed by quite a different scheme. Air flows stream down to the pressure minimum, forming a giant vortex called cyclone. A strong rarefaction exists in the cyclone, and the rotation type is called cyclone rotation.

Vortex cyclones with low velocities usually reach diameters such that the direction of winds in them is assumed to be rectilinear. Such cyclones are usual phenomena in the temperate latitudes of the Earth and they drastically differ from cyclones in the tropics and subtropics, which have tens and hundreds of kilometers in diameter. Vortices in the cyclones are concentrated at shorter distances, and hence they are more powerful. Such tropic cyclones are named typhoons, hurricanes, cyclones, etc. in various regions.

By now, the flow field of a tropic cyclone is known to envelope not only the whole troposphere (up to a height of 15–16 km) but the low layers of stratosphere as well. Under these conditions, an anticyclone prevails above the near-earth center of cyclone, starting from a height of 11 km. The dimension and energy of an anticyclone region are known to strongly influence the properties of the cyclone.

It should be noted that thermal phenomena significantly affect hydrodynamic motion in atmospheric vortices. Although the phenomena strongly affect the conditions of nucleation and maintenance of tropic cyclones, they should be assigned to secondary phenomena. Indeed, such factors as thermal convection, evaporation, and condensation cannot induce strong hydrodynamic motion. The motion can only be caused by a pressure-gradient force; therefore, one should reveal the role of purely hydrodynamic phenomena in the first stage of investigating the giant vortices.

As was noted, cyclone vortices form near a baric minimum. Rotational motion of the atmosphere caused by the vortices results in an air outflow along the radial direction from the center of baric minimum. The outflow makes the rarefaction zone more pronounced, thus favouring the formation of pressure gradient directed from the surrounding medium to the center of baric minimum. Owing to the gradient, two counter-directed flows, that form the contour of a cyclone vortex, appear in the radial direction.

Thus, a cyclone vortex is considered to be a single body with a vortex inside and interacting with the surrounding potential flow. Strong gradients of hydrodynamic quantities can appear at the interface between a cyclone vortex and the surrounding air masses, because the transition from a flow with $\mathrm{rot}\mathbf{V} \neq 0$ to a potential flow with $\mathrm{rot}\mathbf{V} = 0$ takes place here.

Significant gradients of hydrodynamic velocity can cause an unusual behavior of the quantities that are the derivatives of the velocity vector. Let us consider the projection of $2(\mathrm{rot}\mathbf{V})_z = \omega_z$ on the z axis

$$\omega_z = \frac{\partial v}{\partial r} + \frac{v}{r} \tag{1}$$

It follows that the first term may be greater than the second one in the region of an abrupt drop of the tangential velocity v along the radius r, and then ω_z becomes negative.

Cyclone vortices up to 2 km in diameter are called tornado in USA and smerch' in Russia.

The American investigator Gleiser [1] was first to reveal the fact that ω_z changes its sign in a real tornado.

Figure 1 shows ω_z as a function of the radius squared obtained from the actually measured tangential velocities. Gleiser also proposed that the larger the radial region of tornado where ω_z is negative, the more stable and powerful the tornado. Because a tornado forms a relatively narrow zone on the Earth, the radial profile of static pressure in it can be measured by a set of barographs arranged transverse to the earth trajectory of the tornado.

Figure 2 presents a fragment of a barograph tape, where pressure oscillations caused by passing a real tornado through the place where the barograph was set were recorded [2]. Here, the time interval is plotted on the horizontal lines of the barogram grid, and the static pressure is plotted on the vertical lines. Given the velocity of the translational motion of tornado and its transverse dimensions, the time interval of the barogram can be transferred to the radial dimension of tornado, using a special procedure. Therefore, the pressure profile in the barogram

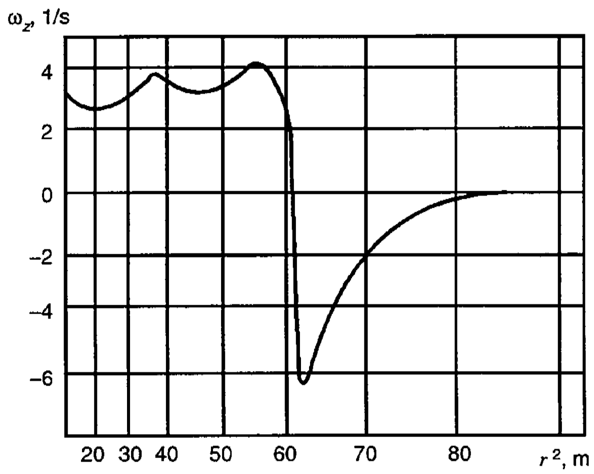

Fig. 1 Distribution of ω_z along the radius of tornado.

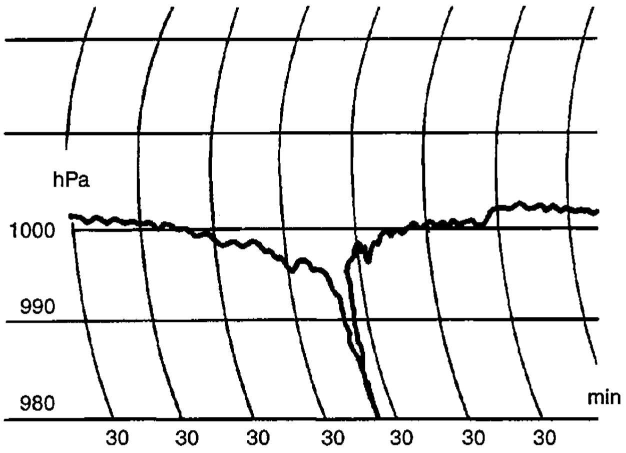

Fig. 2 Barogram in passing a tornado.

represents, on certain scale, the radial profile. That is the reason that ground-based barograms are a reliable tool to determine the rarefaction in cyclone vortices and the character of pressure changes along their radii.

The barogram shown in Fig. 2 qualitatively coincides with the corresponding barograms of hurricanes and typhoons.

Thus, ground-based barograms of cyclone vortices can reveal the following features of the behavior of static pressure along the radius of a vortex: a significant rarefaction in the center, a change of the sign of pressure gradient, and a ring zone where the pressure exceeds atmospheric pressure.

When studying vortices, all investigators first find the profile of tangential velocity as a factor to determine a hydrodynamic flow. Therefore, actual measurements of the quantity is of interest.

Figure 3 gives the velocity profiles of real hurricanes [3]. It is seen that the profiles have two sharp maxima, which does not agree with a model of a classic vortex. Moreover, the first maximum is higher than the second one in some hurricanes and vice versa in others.

In the first case, meteorologists say that the energy of hurricane is concentrated near its center, and in the other case, the energy is distributed over a significantly larger area. Then, the curves in Fig. 3 were smoothed for two hurricanes (*A* – Esther, September 16, 1961; *B* – Daisy, August 27, 1958), and ω_z was determined by numerical differentiation by formula (1).

The results of the operations are given in Fig. 4. It is seen that the value of ω_z for the hurricane *A* has two negative regions; that is, the cellular structure of an

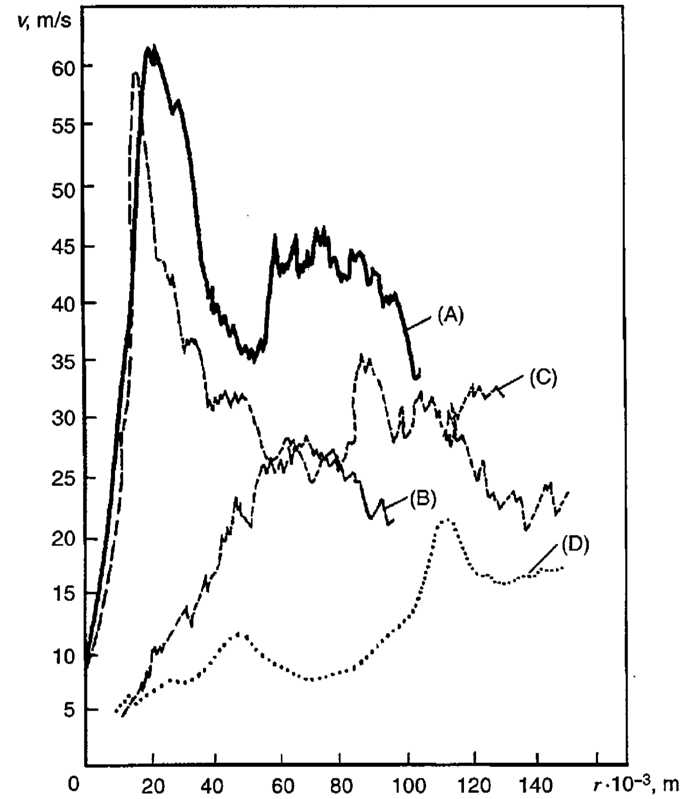

Fig. 3 Radial profiles of tangential velocity in hurricanes: A, Esther, September 16, 1961; B, Daisy, August 27, 1958; C, Ginger, September 26, 1971; and D, Hellen, September 24, 1958.

insulated trailing swirl takes place (Fig. 4a). This value for the hurricane *B* is always positive (Fig. 4b), but it is not powerful [3].

Another question is of interest. What are the boundaries (radii) of the vortices considered? Some meteorologists believe that the boundaries coincide with the radius of maximum tangent wind. From the hydrodynamic point of view, the boundary of the vortices should be the radius, where the value ω_z changes its sign after the last maximum. Here, a vortex becomes insulated from the surrounding medium because of an abrupt drop of the tangent velocity and interacts with the medium as a unit. Hereafter, we shall call the vortex the insulated trailing swirl or the single vortex.

Starting in the 1950s, aviation was used for performing actual measurements in hurricanes and typhoons. In [4], the treated and checked data of searching

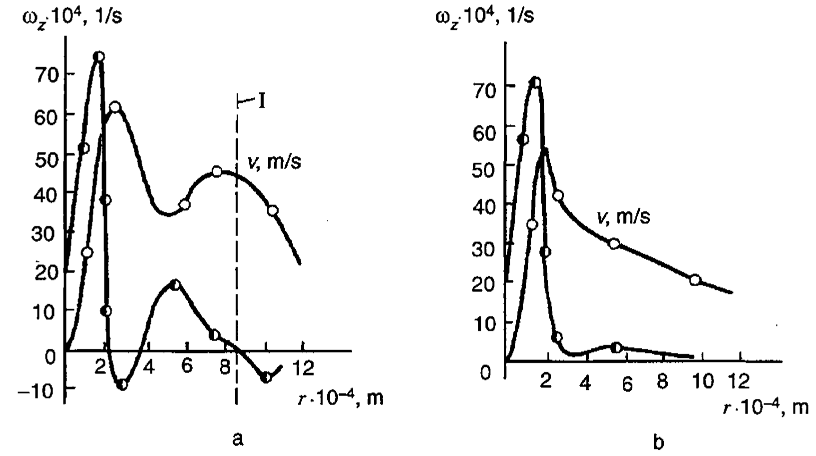

Fig. 4 Radial ω_z profiles in real hurricanes: I, vortex boundary.

flights in hurricanes in 1957–1969 are given. The actual measurements were performed in 21 hurricanes during 41 hurricane days. These data are unique because they contain simultaneous measurements of the wind velocity, temperature, and pressure up to the scale of heap clouds. All experimental data on 21 hurricanes were averaged, and a model of the so-called averaged hurricane is given. According to this model, a few maxima exists in the radial profile of the tangent velocity of wind at a high troposphere level (525 hPa), and the only maximum is clearly pronounced at a low level (900 hPa). At the high level, the absolute value of the first clearly pronounced maximum is smaller than that of the second maximum, which means that the kinetic energy is concentrated far from the center. At the low level, the kinetic energy is concentrated closer to the center of the hurricane. The particular feature of variation of the profile of the tangent velocity of wind depending on the height remains for deepening and filling hurricanes.

The accuracy of measurements of the radial component of the wind velocity was especially thoroughly analyzed in [4]. It was found that even small changes in the position of a plane can cause significant changes in the radial component of the wind velocity.

A construction of the radial profiles of the pressure drop (D) between the pressure in the center of hurricane and the pressure in the undisturbed surrounding medium at the given troposphere level of an averaged hurricane has received much attention in [4]. Recall that D is the difference between the absolute and barometric heights. The barometric height is the height that corresponds to the pressure measured in the standard tropic atmosphere.

It follows from [4] that the pressure in a hurricane at the low troposphere

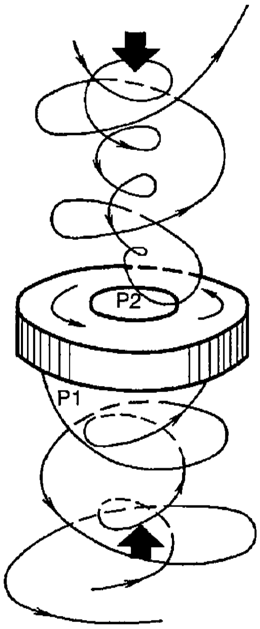

Fig. 5 Hydrodynamic model of a single vortex.

level (900 hPa) is lower than that in the undisturbed surrounding medium, and the pressure gradient changes its sign in the center of vortex and at its periphery. As the troposphere level increases, the pressure inside a hurricane begins to exceed that in the surrounding medium first at the periphery and then along the whole radius of the hurricane.

The behavior of the radial pressure profiles caused by an increase in the troposphere level means that the hurricane is a giant vortex in whose upper part secondary flows forcing the air into the vortex and vice verse in its lower part. In other words, a baric maximum takes place in the upper part of an atmospheric vortex, and a minimum, in the lower part.

Based on the facts, Bubnov [5] gave the following hydrodynamic model of an atmospheric vortex (Fig. 5).

A vortex mass of air and clouds forms a vortex ring at the troposphere level, where the concentration of clouds is maximum. The vortex ring entrains the air adjoining the ring from above and below in the rotational motion. In so doing, a particle above the ring moves along an inner spiral from top to bottom. When the particle reaches the ring, it is repelled from it and goes up along an outer spiral, by remaining its direction of rotation. However, the gravity force does not allow it to achieve the initial height. As a result, the air above the ring becomes denser, and the pressure p_2 in this part of vortex would be higher than that in the undisturbed atmosphere of the given troposphere level. In other words, the influx in the vortex is greater than the efflux.

The converse behavior of flows is characteristic for the air mass below the ring (Fig. 5). Here, an air particle moves along an inner spiral from bottom to top, and an outer spiral forms a descending flow. A significant rarefaction occurs inside the vortex, which leads to that the pressure p_1 below the vortex ring is lower than that at the periphery.

Thus, an atmospheric vortex combines the cyclone and anticyclone rotations along its height.

The absolute pressure p_1 above the ring may be smaller than that below the ring (p_2). In this case, a narrow layer with a flow directed along the axis from the ring from the top down can form along the vortex axis.

A hypothesis for the existence of the vortex ring was supported by the blocking phenomenon discovered by the American investigator Granger [6]. The phenomenon lies in the fact that a cloud structure surrounding an atmospheric vortex hinders centrifugal removing of air masses because it is denser than air.

Modern engineering has a wide class of machines and units that operate on the principles of the vortex motion of liquid or gas. In the devices, single vortices with the hydrodynamic motions that agree with the model in Fig. 5 are formed. The vortices only differ in the design principles of the formation of the vortex ring. Thus, the vortex ring is formed by an impeller in turbomachines, owing to the tangent inlet of air or liquid in vortex chambers and centrifugal atomizers, owing to pressure nonuniformities along the height and spinning angle in drawing off liquid through bottom holes, and by a thin disk slipped over a shaft of a device in the end gap of a hydrostatic thrust journal.

In many devices, a vortex is surrounded by a cylindrical surface with boundary layers forming near it because of the interaction between the vortex and the lateral and end walls. The vortex is the so-called external flow relative to the walls, that form the structure of flows in the boundary layers. Therefore, the radial pressure drop in the vortex mainly contributes to the resistance force of such devices rather than friction losses in the boundary layers.

Obviously, liquid particles circumscribe concentric circles in the plane $r\varphi$ (Fig. 5). We consider two perpendicular to each other rods *ab* and *cd* (Fig. 6)

When turning by an angle φ_1, all points of the *cd* rod have the same velocity $V(r)$ because the liquid particle in this case moves as a solid at the distance $rd\varphi_1$ with the angular velocity ω_1,

$$\omega_1 = \frac{V(r)}{r} = \frac{d\varphi_1}{dt} \tag{2}$$

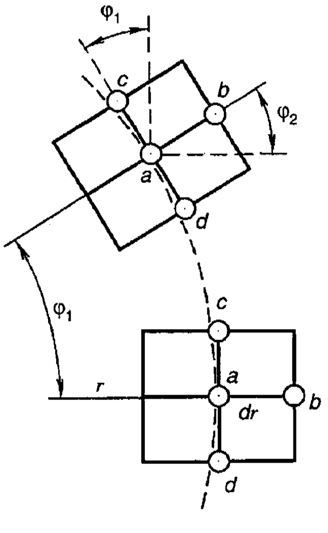

Fig. 6 Kinematics of a liquid particle in a vortex.

Under these conditions, point *a* in the *ab* rod moves at a distance of $vdt = rd\varphi_1$, whereas point *b* moves at another distance because its velocity is

$$v + \frac{\partial v}{\partial r}dr$$

Hence, the displacement of point *b* is

$$\left(v + \frac{\partial v}{\partial r}dr\right)dt$$

The difference in the displacements of the points *a* and *b* is

$$\Delta r = \frac{\partial v}{\partial r}drdt$$

Thus, the *ab* rod rotates about the point *a* by an angle of

$$d\varphi_2 = \frac{\Delta r}{dr} = \frac{\partial v}{\partial r}dt$$

The angular velocity of the *ab* rod about the point a

$$\omega_2 = \frac{d\varphi_2}{dt} = \frac{\partial v}{\partial r} \qquad (3)$$

characterizes the rotation of the liquid particle about its geometric center.

Hence, the derivative of the circular velocity of the vortex with respect to radius characterizes the rotation of the liquid particle about its geometric center.

We introduce the concept of the mean angular velocity of rotation:

$$\omega_z = \frac{1}{2}(\omega_1 + \omega_2) = \frac{1}{2}\left(\frac{\partial v}{\partial r} + \frac{v}{r}\right) \qquad (4)$$

If $\partial v/\partial\varphi = 0$, $\omega_z = \frac{1}{2}(\mathrm{rot}\mathbf{V})_z$. Thus, the radial profile ω_z in the vortex characterizes the mean angular velocity of rotation of the liquid particle, which consists of the rotation about the central vortex axis and about the geometric center of the particle. Note that the rotation about the vortex axis coincides with the circular velocity, whereas the rotation about the geometric center is counter-directed with respect to the circular velocity. Therefore, regions with positive and negative values of ω_z can appear in the radial profile ω_z.

We consider the motion of the liquid particle at the place of the vortex, where its circular velocity decreases. The velocity is usually inversely proportional to the radius, i.e.,

$$v = c/r \qquad (5)$$

Then, we have

$$\omega_1 = c/r^2$$

$$\omega_2 = -c/r^2$$

The last two formulas mean that the liquid particle rotates about the vortex axis by an angle of $d\varphi_1$ in the time *dt* and by the same angle about its geometric center but in the opposite direction. As a result, the resulting mean angular velocity ω_z is zero, which means the absence of vortex motion. Therefore, the translational motion of the liquid particle along a circular path takes place. We shall call the radius where $\omega_z = 0$ in the radial profile ω_z the radius *R* of single vortex.

Now, we assume that the circular velocity decreases as

$$V = c/r^n \tag{6}$$

after its maximum.

In this case,

$$\omega_1 = \frac{c}{r^{n+1}}$$

$$\omega_2 = -\frac{nc}{r^{n+1}}$$

Then, for the mean angular velocity of rotation we have:

$$\omega_z = -\frac{c(n-1)}{2r^{n+1}}$$

If $n > 1$, $|d\varphi_2| > |d\varphi_1|$. The latter means that for $r > R$ the mean angular velocity of rotation does not coincide with the direction of the circular velocity, and the reverse motion of the liquid particle along the circular path takes place.

Thus, the circular velocity decreases as (6) in full-scale vortices (Fig. 4) where $\omega_z < 0$.

We assume that a single vortex does not exchange its heat with the surrounding medium. Then, in the framework of isoentropic process, the first law of thermodynamics applied to ideal gas gives the following relation between pressure (p) and temperature (T) changes

$$dp = \rho c_p dT \tag{7}$$

where ρ is the density of gas, and c_p is the heat capacity of gas at a constant pressure.

The pressure in the anticyclone part of a single vortex increases from the periphery to its center. Hence, according to (7), this behavior leads to an increase in the temperature in the vortex, which can account for warming up of air masses caused by their anticyclone rotation. It obvious, by now, that the cyclone rotation would cool the air masses. Interestingly, the French investigator Rank discovered the vortex effect of energy separation of gases in 1931 and experimentally showed that a rapidly rotated gas flow in a circular tube has a nonuniform radial profile of temperature: gas near the axis is cooled, and that at the periphery is heated.

Nowadays, many original engineering devices were created on the basis of this effect, but from the point of view of the described phenomena that occur in a single vortex, this effect is obvious.

1.2 Laboratory Model of the Vortex

In the last few years, various types of vortex generators were designed for laboratory modeling of tornados and cyclones. The generators are mainly differ in the design of elements that create the axis convection and the angular momentum. The angular momentum is usually transferred to gas in rotating the walls of a vessel or a swiller of the blade-wheel type. Sometimes, a vortex is created by a tangent inlet. In order to reproduce axial flows, air intakes creating pressure differential along the vortex axis are used. Moreover, devices, where flows are created by a temperature difference along the vortex axis or by electric conductivity, are used.

In order to model a single vortex, the model of a vortex generator shown in Fig. 7 was used in [7–10]. Here, a single vortex is formed by the rotation of a four-vane swirler $R_1 = 0.075$ m in radius, which is located in a cylindrical shell with the inner radius $R_2 = 0.105$ m. Two characteristic dimensions of the vortex generator are: the clearance $S = 0.03$ m and the height $h_1 = 0.035$ m that determines the length of the upper anticyclone vortex.

The centrifugal force removes the air in the lower part of the swirler along the radius, and the air is flung down by the lateral walls of the shell. The last cir-

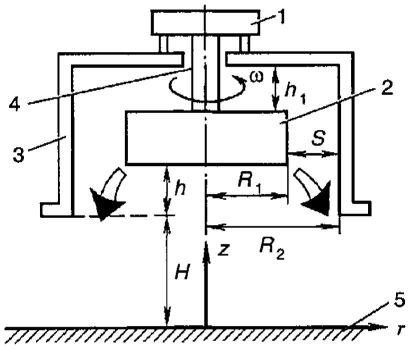

Fig. 7 Laboratory model of a vortex: 1, electric heater; 2, four-vane swirler; 3, shell; 4, motor shaft; and 5, bearing surface.

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