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Vortex structure of swirl flows

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ABSTRACT

The paper presents some results of investigations related to the problem of studying the mechanisms of vorticity generation and the conditions for formation and stability of determinate vortex structures. This problem is one of particular importance in the field of fundamental investigations of complex vortex flows. At the same time the problems of studying the physics and topology of complex vortex and swirl flows are topical for diagnostics of some hazardous geophysical processes such as hurricanes, tornados, tsunami, change in the direction of oceanic currents, etc. It is shown that the main mechanism for appearance of steady-state vortex structures in swirl and curved flows is connected with the process of helicity generation. The equation of helicity generation rate for dynamical liquid system is obtained to determine the critical conditions for flow field alteration. The convenience of theoretical analysis on the base of helicity generation rate equation consists in a possibility to predict the appearance of steady large-scale structures from solution of a single scalar equation written with respect to the scalar value of helicity. Application of developed model of vortex motion in swirl flows is demonstrated for two hydro-mechanical systems: in case of Taylor instability in annular channel, and for flow of coolant in collector of nuclear reactor. The paper describes a new approach for prediction of conditions for appearance of large-scale steady-state vortex structures in complicated vortex and swirl flows.

1. Introduction

Swirl flows attract ever growing interest of researchers due to the wide range of engineering applications of the special properties of swirl flows in power-engineering and heat-exchange equipment for power generation, aerospace, chemical and oil-processing industry, transport and heat power engineering.

As it was mentioned in analytical review [1], among numerous works devoted to various aspects of theory, simulation, experimental investigation, and practical applications of swirl flows, pioneering studies in the field of thermodynamics of swirl flows were fulfilled by Novikov and associates [2–4]. These studies resulted in the discovery and interpretation of the effect of maximal flow rate of fluid swirl flow [3]. Based on the experimental results, it has been demonstrated that the critical velocity of translational motion of swirl flow of a viscous incompressible fluid is equal to the propagation velocity of long centrifugal waves.

Many evidences of the existence of complicated internal vortex structure of swirl flows are widely known. First of all there are natural phenomena, such as tornado, hurricanes, astrophysical objects. In engineering devices the swirling of a flow results in a large-scale effect on all parameters of the flow field and appearance of determinate vortex structure of the flow. In the monograph [4] two essential aspects of recent investigations of complicated vortex and swirl flows are considered. The first of them is description of simulation problems of hydrodynamics and heat transfer of complicated swirl flows of viscous incompressible fluid in channels with swirl-flow devices. The second one is the revelation of common physical laws of turbulent swirl flows for prediction of appearance of large-scale steady-state vortex structures. Capabilities of the elaborated in the work [4] calculative methods for annular channels and tubes with swirl-flow arrangements of arbitrary geometry allow to determine friction factors, intensity of flow swirling and heat transfer coefficients in channels with various swirl-flow devices and to find their optimal geometry.

The visualization pictures of vortex structures observed in engineering devices are presented, for example, in monographs [5,6]. In the book by Alekseenko et al. [5] knowledge about concentrated vortices observed in nature and technique is systematized. Models of vortex structures are used for interpretation of experimental data. Gupta et al. in monograph [6] consider a wide range of problems associated with practical application of swirl flows, and give much attention to effect of vortex structures in swirl flows on the process of combustion and fission in chemical engineering, power and engine plants. In their paper Arbuzov et al. [7] produce the experimental results indicative of the existence of large-scale spiral vortices in a swirl Ranque flow (Ranque effect).

Large-scale vortex structures in the turbulent flows confined by impenetrable surfaces may be created as a result of a sudden

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Nomenclature

Eu	Euler number
Fr	Froude number
G	flow rate
H	helicity
Ho	homochromaticism criterion
k	vorticity intensity
P	pressure
$\vec{P}_v$	density of volume forces
Re	Reynolds number
$\vec{u}$	velocity
u_r	radial velocity
u_z	longitudinal velocity
u_φ	tangential velocity
Greek symbols	
ν	kinematic viscosity

change in the value and direction of the flow velocity, upon a change in the geometry of the flow section of channels, if a separation or a turn of the flow occurs, and in other cases.

Analysis of current status in the field of simulation of complex vortex and swirling flows, carried out in the review [1], showed that application of turbulence models of different classes to predict behaviour of swirl flows can't give adequate results, and continuing investigations demonstrate that the physical nature of swirl flows still remains unperceived. In particular, a number of questions to be answered, such as an appearance of the internal vortex structure in restricted swirling flows, a correlation between the spatial delimitation of the regions of stabilization and destabilization of flow for the different swirling intensity, and a transformation of the turbulence structure as a result of appearance of the large-scale recirculation zone in highly swirling flows.

The use of other modern simulation methods based on consideration of Navier–Stokes equations, such as direct numerical simulation (DNS), large eddy simulation (LES) and "hybrid" methods [1], hardly can lead to new capabilities. The main obstacles to the use of the methods mentioned include the need to employ huge computational resources and, at the same time, the limited resolution of grid division. Another unresolved problem is absence of a universal method of the description (for subgrid-scale simulation) of small-scale turbulent transfer for different cases, such as rotational or shear flows, flows in the vicinity of solid surfaces, and transient regimes.

In the present paper the main attention is concentrated on the problem of studying the mechanisms of vorticity generation and the conditions for the formation and stability of determinate vortex structures.

2. Critical transitions in swirl flows of a single-phase liquid

Despite the variety of conditions for appearance of determinate vortex structures, analysis of the available comprehensive experimental material leads to a conclusion about existing the general laws of formation and topological features of arising large-scale vortices.

For the analysis of critical regeneration conditions for flow field of coolant the results of analytical solution for helical flow in annular channel were used. The solution was obtained in the work [8] for a vortex flow obeyed the law of helical motion. In that case the following equality takes place:

$$curl\ \vec{u} = k\ \vec{u}, \tag{1}$$

where k is the scalar value having the dimensionality of curvature (m^{-1}). Such an approximation is justified because at high Reynolds numbers corresponding to operating flow rates of liquid–metal coolants in nuclear reactors the value of total velocity in the channel cross-section is leveled out, the Bernoulli integral becomes approximately the same for all the streamlines, and the flow can be considered as a helical one.

In works [4,8] it was shown that under condition of helical movement of inviscid liquid (1) equation of continuity is satisfied automatically, and for the analysis of vortex structure of an axisymmetric flow it is possible to use the equations:

$$-\frac{\partial\ u_\varphi}{\partial\ z} = k\ u_r, \tag{1a}$$

$$\frac{1}{r}\,\frac{\partial(ru_\varphi)}{\partial r} = k\ u_z, \tag{1b}$$

$$\frac{\partial\ u_r}{\partial\ z} - \frac{\partial\ u_z}{\partial\ \mathrm{r}} = k\ u_\varphi, \tag{1c}$$

where u_φ, u_r and u_z are the tangential, radial and longitudinal velocity components correspondingly.

Substituting (1a) and (1b) in (1c), we can receive the equation for tangential velocity component:

$$\frac{\partial^2 u_\varphi}{\partial z^2} + \frac{\partial^2 u_\varphi}{\partial r^2} + \frac{1}{r}\,\frac{\partial u_\varphi}{\partial r} + u_\varphi\left(k^2 - \frac{1}{r^2}\right) = 0, \tag{1d}$$

which can be used for description of vortex structure of helical flow.

2.1. An example of hydrodynamic stability crisis

One of an obvious purposeful examples of fluid instability accompanied by reconstruction of flow vortex structure is an appearance of the Taylor's vortices (Fig. 1a). These toroidal vortices arise in annular channel formed by two coaxial cylinders, when outer of them is fixed while inner one is revolved on its axis with angular velocity exceeding some critical value corresponding to critical Taylor number defined by Schlichting in the monograph [9] as $Ta_{cr} = 41.3$.

The conditions for appearance of Taylor–type vortex structures can be realized for the flows of liquid–metal coolants in annular sections of different collectors. The experimental data generalized in paper [10] show that the common feature for the dispensing collector systems of such nuclear reactors as pressurized water reactors (PWR) and liquid metal fast breeder reactors (LMFBR) with water and liquid–metal coolants is a relatively low intense agitation of the coolant flows from different loops. The presence in turbulent flows of the stable local formations impeding coolant agitation at the core entrance can lead to reactivity accidents. The combined operation of centrifugal pumps may be a plausible reason for the appearance of tangential velocity in collectors due to availability of radial vorticity component in the flow.

The proposed simulation method is based on the fact that flow region can be split into the wall zone, where effect of viscosity plays a dominant role, and the inner zone characterized by a constant Bernoulli integral for all streamlines, where the flow may be considered as a helical one. The description of the helical flow can be fulfilled by using the theory developed by Gromeka [11].