KAPITEL 3 / *CHAPTER 3* [3]
FEATURES OF TRANSPORT IN OPEN CHANNELS AND STABILITY CONDITIONS OF STRATIFIED FLOWS

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Introduction and problem statement

Water streams and natural reservoirs are used for drinking water supply and land irrigation. Having analyzed the issue of ecological processes of the aquatic environment, it was proposed to consider channel processes from a physicochemical point of view, as well as transport phenomena. Solving such a problem from the position of the transport phenomenon in living organisms can open up new opportunities for considering and solving a certain class of problems of channel flows. Taking into account the coefficients of transport, diffusion, viscosity and thermal conductivity is relevant in complex rheological systems, which also include mountain rivers and channels.

The issue of transport in living organisms was studied by such famous scientists as E. Lightfoot and others [1, 2]. It is believed that life on Earth exists in three spheres, namely in the carbonosphere, atmosphere and stratosphere, the connections between which are carried out by means of water [3]. Water in different aggregate states is a means for the formation and change of the composition of macroelements that it carries. Of course, the water of streams generates energy, which is directed opposite to the flow of water. The birth of organic substances is accompanied by the binding of oxygen. When these two opposite processes intersect at a certain point, energy is released. Therefore, there are constant changes in individual microclimatic conditions, that is, changes in the quantitative and qualitative composition of the main chemical elements [4].

The result of these continuous mutual processes is a change in the state of different types of water in specific zones. As well as a constant transformation of vegetation types that adapt to water, which is constantly moving by the force of internal

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interactions. Internal energy interactions are opposed by the influence of water weight. Changes in the magnitude of these component forces inevitably cause constant raising and lowering of water particles, which is called water pulsation. Each neoplasm originated in the smallest processes. Development in the early stages can reach the end only if the intraterrestrial processes operate correctly. According to the law of nature, each more perfect type of plant comes from another, more primitive one. The transport medium of substances, as well as a means of storing and transmitting information about life processes, are primarily underground waters, which are reached by plant roots. The movement is regulated by the temperature difference, due to which internal metabolic processes occur with the participation of basic elements [2, 4].

So, for the movement of water, the impulse is the product of interactions between opposing processes that are constantly present in water. Due to the constant resistance that arises as a result of interactions between carbon and oxygen, temperature fluctuations occur again, and with them the impulse to movement. That is, the pulsations of water, which thus sometimes dissolves salts and other substances, and sometimes accumulates, transports and transforms them. The essence and meaning of these eternal transformations in the creation and preservation of various types of plants and physical forms, which are a means of storing and transforming various types of energy. The difference in potentials, as well as the constant difference in values between the temperature of the internal and external environment are only forms of energy that constitute the water cycle and provoke a continuous circulation [5, 6].

Every body needs an internal energy from which it is built, thanks to which it is transformed. When the body disintegrates, then these energies from which it was created are released. When energy is released as a result of the disintegration of the body, water willingly absorbs it, together they circulate on the surface of the Earth, and the energy finds new life. Thus, continuous formations and transformations are present everywhere. Every material form of life is always a reflection of an immaterial form consisting of light, heat and radiation [2, 4].

Each change in the processes of internal and external exchange as a whole changes the density and intensity of the internal radiation of water. Thus, the direction in which it moves during life changes. Violation of the natural laws of internal and external conformations leads to a violation of the global evolution of life. The disappearance of water or the transformation of substances is a very important warning sign, since the nature of water also changes depending on its internal composition. At the same time, the nature of all life forms, including humanity, also changes. The quantitative reduction of plant species and, above all, the deterioration of higher plants leads to the physical and moral degeneration of humanity. These are only obvious consequences of changes in the physicochemical composition of water and the destruction of the lithosphere, which occurs as a result of the destructive activities of humanity on Earth [7].

3.1. Characteristics of fluid movement in open channels and canals

The main feature of waves moving in open channels is their ability to carry significant fluid flows, which is why they are called displacement waves. Such waves are divided into discontinuous and continuous [2].

The simplest form of unsteady motion is considered to be a wave in one direction, when the flow rate only increases or only decreases. When the liquid level increases, the wave is called positive, and when the level decreases, it is called negative. In addition, a wave that propagates upstream is called reverse, and downstream is called direct. Depending on the ratio of these features, there are four main types of waves [7, 8].

Reverse (negative) wave, or outflow wave. It occurs when the flow rate increases in the final section, transfers the increase upstream and causes a decrease in the liquid levels in the channel. The front of the wave, moving along the flow at a certain speed, is called the wave front, which causes quite sharp changes in the flow.

The profiles of a direct positive wave lying at higher elevations will move faster than those located downstream. As the line moves away from the origin, the deviation of the flow and depth from their values during steady motion decreases. This phenomenon is called spreading, or dynamic transformation of the wave.

In steady motion, for each section in the flow, there is a unique dependence of the flow rate on the depth in a certain cross section $Q = f(h)$. And when the flow is unsteady, along with the increase in flow, the slope of the free surface increases, which leads to a decrease in depth. The obtained equation is the main differential equation of the unsteady planar fluid motion in open channels and channels. The dependences, first obtained in 1871, are called the Saint-Venant equations [7].

These equations contain two inertial terms that take acceleration into account. One of them, $\frac{V}{g}\frac{dV}{dl} = \frac{d}{dl}\left(\frac{V^2}{2g}\right)$, expresses the convective acceleration during steady non-uniform motion, and the second, $\frac{1}{g}\frac{dV}{dt}$, is the local acceleration that occurs during unsteady motion.

Unsteady motion is also characterized by the parameter of unsteadiness $П_{н.с.} = \frac{h}{V^2}\frac{dV}{dt}$. In the case when $П_{н.с.} < 0,5$, the head losses along the length in each section and at a certain point in time are determined by the formula of uniform motion

$$i_f = \frac{Q^2}{F^2 W^2}. \qquad (1)$$

When solving the Saint-Venant equation, it is necessary to derive the dependencies $h = f_1(t;l)$ and $Q = f_2(t;l)$. However, the exact solution of these equations is almost impossible, given their complexity. These equations are solved in the simplest cases, and for more complex ones, the method of numerical integration is used, which is implemented thanks to computing technology. In addition, a number of simplified methods are used, which are based on various assumptions.

Stratified flow is the phenomenon of the influence of fluid density heterogeneity on the process of its motion or on pressure, velocity, and tangential stress diagrams. The terms "stratification" and "layering" have the same meaning. The theory of the motion of stratified flows is widely used in energy, hydraulic engineering and hydrology, water supply and drainage, and when considering issues of air and water basin protection.

The change in the density of a liquid can be caused by changes in the depth of the flow, the concentration of suspended or dissolved particles and temperature. Based on this, flows are classified by mechanical, chemical and temperature stratification. Mechanical stratification is characterized by the value of the difference in density with depth, and chemical by the percentage of density. In temperature stratification, the difference in density is small, namely $\frac{\Delta\rho}{\rho} \leq 0,005$.

In the field of action of gravitational forces, or in the vertical direction, the inhomogeneity of the liquid leads to the emergence of Archimedean forces in the liquid, due to which heavier particles move downwards and lighter ones upwards. At the same time, the action of Archimedean forces, as well as other hydrodynamic forces, causes a change in the energy of the turbulent flow. With an increase in density depending on the increase in depth, such a liquid movement is called statically stable, or with direct stratification. And in the case when the depth decreases, then statically unstable, or with reverse stratification.

In the case of statically stable stratification, Archimedean forces inhibit the turbulent movement of large particles upwards and lighter particles downwards. Then the energy of turbulence is converted into potential energy of position. That is, direct stratification contributes to the suppression of turbulence. Conversely, in reverse stratification, Archimedean forces enhance turbulence due to the presence of vertical convective currents, which causes an increase in turbulence.

In direct stratification, under certain conditions, a region of viscous flow is formed in the flow, which divides the turbulent flow into zones. Such regions are called density jump layers, and in the case of temperature stratification - thermoclines. In real conditions, the thickness of the separation layer is relatively small compared to the thickness of density flows. Therefore, we do not speak of a layer, but of a separation surface. Although this definition is more appropriate for liquids that are not completely miscible.

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Depending on the magnitude of the local velocity and density gradients, statically stable stratified flows are divided into two types:

1. Flows with a continuous change in density with depth;

2. Pre-layered (or multilayered) flows with a density discontinuity at the separation surface.

3.2. Stability conditions for stratified flows

The motion of a stratified flow is described by a system of differential equations, which include the Reynolds equation of fluid motion, flow continuity, and diffusion. For a detailed consideration of flows, the basic similarity criteria are used [2]:
Reynolds number

$$\mathrm{Re} = \frac{Vh}{\nu}, \qquad (2)$$

and the Froude density number

$$F_r^{'} = \frac{V}{\sqrt{gh\frac{\Delta\rho}{\rho}}}, \qquad (3)$$

where respectively h, V – depth and flow velocity, same density.

The Reynolds number is a characteristic of frictional forces and inertial forces, and the Froude density number takes into account the influence of gravitational and inertial forces in the middle of the stratified flow. If the density of the upper layer ρ_1 can be neglected compared to the lower ρ_0, i.e. $\left(\frac{\rho_0 - \rho}{\rho_0}\right) \approx 1$, then the Froude density number becomes ordinary. This phenomenon is observed during the interaction of the lower air layer of the atmosphere and the upper liquid layer in a reservoir [4, 8].

When calculating stratified flows, the problem of determining the conditions that ensure their stability constantly arises, therefore this task includes three independent tasks:

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1. Determining the conditions under which turbulence occurs in the region of the separation surface;

2. Estimating the conditions necessary to maintain unquenched turbulence in a flow inhomogeneous in density;

3. Studying the influence of external factors on the stability of stratified flows.

The change in the parameters of flows near the surface occurs due to the action of tangential stresses on the boundary between flows with different densities, as well as under the influence of external factors.

Kelegan's experiments revealed that the loss of stability of internal waves at the interface of flows with different densities occurs when critical values of the Kelegan criterion K_e parameters are reached

$$K_e = \frac{\left(\nu_0 g \frac{\Delta\rho}{\rho} \right)}{V_1} = Ke_{kp} = 0{,}178 \quad . \tag{4}$$

The Keleghan dependency is sometimes presented in this form

$$Ke = \mathrm{Re}\, Fr'^2 = Ke_{kp.} \quad . \tag{5}$$

The stability criterion is derived based on the assumption that the transition from a two-layer flow with a boundary layer to a flow with turbulent movement occurs abruptly. In addition, the viscosity of the liquid in the vertical direction with the flow depth was not taken into account. This assumption is relevant to chemical stratification, but its use for mechanical and temperature stratification is also possible.

Further experiments revealed that the transition from a flow with density stratifications with a stable interface to a flow with turbulent mixing occurs smoothly and also depends on the degree of development of internal waves at the interface.

As a result, the stability condition of the density layering takes the following form

$$F = \mathrm{Re}_\delta\, Fr'^2_\delta = F_{kp.} \quad , \tag{6}$$

where the Reynolds number and the Froude number will be equal

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$$\mathrm{Re} = \frac{\Delta V \delta}{\frac{\rho_1 V_1 + \rho_0 V_0}{\rho_1 + \rho_0}}; \quad Fr_\delta^{'} = \frac{\Delta V}{\sqrt{g \frac{\Delta \rho}{\rho} \delta}}. \qquad (7)$$

These values are obtained for the dynamic boundary layer separating flows of different densities with thickness and velocity shift at the interface - ΔV .

When the developed boundary layer covers the entire thickness of the surface between the layers, and the lower one is stationary, then $\delta = h_1$ та $\Delta V = V_1$.

The most characteristic forms of flow in the boundary layer zone are considered to be:

1. Laminar flow, the limits of its existence are defined as

$$F \le F_{kp} \approx 150. \qquad (8)$$

2. Motion with regular standing internal waves

$$F_{kp1} \le F \le F_{kp2} \approx 500. \qquad (9)$$

3. Movement with the advantage of irregular long waves

$$F_{kp2} \le F \le F_{kp3} \approx 800. \qquad (10)$$

4. Movement with the advantage of short unstable waves

$$F_{kp3} \le F \le F_{kp4} \approx 1650. \qquad (11)$$

5. Turbulent mixing

$$F > F_{kp4}. \qquad (12)$$

In the practice of designing and operating water management facilities, namely, water discharge from thermal and nuclear power plants, discharge of wastewater into reservoirs, inflow of salt water into river mouths, etc., stratified flows are formed, which are assumed to be two-layer. In this case, the characteristics of each layer are considered separately without significant error and the turbulent exchange between them is neglected [7].

The main issue in calculating such flows is determining the hydraulic friction coefficient on the separation surface λ_p, which is found by the following formulas

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$$\lambda_p = 2,4F^{-0,9} \text{ at } F \le F_{kp1}; \tag{13}$$

$$\lambda_p = 0,08F^{-0,54} \text{ at } F \ge F_{kp4}. \tag{14}$$

For the transition zone, when $F_{kp1} \le F \le F_{kp4}$, calculating λ_p, it is recommended to use the graph constructed by Y. Georgiev, where the Reynolds number and the Froude number are equal

$$\mathrm{Re} = \frac{VR}{\nu}; \qquad Fr_R^{'} = \frac{V^2}{gR\frac{\Delta\rho}{\rho}}. \tag{15}$$

Summary and conclusions

Having analyzed the issue of ecological processes of the aquatic environment, it was proposed to consider channel processes from a physicochemical point of view, as well as transport phenomena. The dependencies that describe unsteady fluid flows in open canals and channels and the movement of stratified flow were considered. Based on the conducted research, the features of the characteristics of fluid movement in open channels and canals, as well as the conditions of stability of stratified flows, were analyzed.

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