Study of the Flow Structure Stability in a Multi Vortex Contact Device

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***Abstract*— In this scientific paper, the authors studied the dependence of the change in the relative height of vortex formation on the dimension of the Field tube structure by means of numerical simulation, as well as the dependence of the change in the relative height of vortex formation on the fluid medium flow rate. Making several holes in the base contributes to the appearance of numerous uniform vortices in the air or water environment, which affect the intensity of heat transfer. Numerical simulation in the ANSYS Fluent software program was carried out to study this device. Analysis of the experimental data obtained showed that an increase in the angular rate leads to an increase in the height of the vortices. The relative height of the vortices practically does not depend on their diameter.**

Keywords*— *vortex structures, the Field tube, holes, heat transfer (release), heat exchange, vortex flow.

I. INTRODUCTION

As of today, a lot of industrial facilities use the devices with vortex flows to increase the efficiency of the processes of separation of heterogeneous systems and heat-mass exchange. Therefore, research in this area among foreign and domestic authors is still relevant to this day.

For example, one of these devices is the Field tube. The invention relates to mechanical engineering, namely to the Field tubes for high-temperature tube heat exchangers, for example, for direct-flow steam generators of nuclear power plants with a heating liquid metal coolant. On this topic, the results of experiments on the flow simulation in the annular channel of the heat exchanger and the results of calculation according to the original methodology, developed by the author, were given [1].

The authors of the article [2] proposed a method for improving the heat exchange process using a magnetic vortex generator that creates a swirling flow of nanofluid in heat exchangers. The swirling flow due to the influence of the magnetic field destroys the boundary layer and increases the heat transfer up to 320% with a slight increase in the pressure drop. Later in another work [3], using the proposed method, the researchers of the previous article were able to achieve an increase in the hydrothermal and exergetic characteristics of heat exchangers up to 90% and 33%, respectively.

In [4] the author considers the problem of reliability and durability of heat exchangers of closed gas turbine installations. One of the ways to solve this problem is the use of a Field pipe. It is shown that when using the developed method of numerical calculation of the "gas-dynamic" protection of the Field pipe, in terms of thermal efficiency, this device can approach a countercurrent heat exchanger.

Heat transfer through narrow channels with a gap is widely used in various branches of mechanical engineering, such as aerospace and aviation technology, microelectronics and nuclear reactors. However, in a narrow channel with a gap, foreign substances are deposited that pollute the heat exchange surface during the movement of a high-speed liquid, which leads to deterioration of heat transfer conditions. In this regard, the author of the work [5] considered a narrow-band two-phase heat transfer technology with significant efficiency of heat exchange intensification. The main mechanism of heat transfer is based on the evaporation of a microfluidic film at the bottom of compressed and deformed gas bubbles.

In the study [6], in order to control the flow field to increase heat transfer, a cylindrical partition was inserted into the tank. The partition creates an annular gap around the tank wall, in which a copper coil-heat exchanger is placed. The partition affects the transient heat transfer, the temperature of the supplied water and the efficiency of the heat exchanger. The partition increases the convective heat transfer on the storage side to the heat exchanger by 20%. This increase is due to higher storage fluid velocities in the heat exchanger.

Another promising direction is the development of combustion devices for pulverized coal fuel, aimed at intensifying the processes of mixing and ignition, increasing the completeness of fuel combustion with reduced dimensions of the combustion chamber and reducing emissions of toxic combustion products [7]. In this scientific paper on the basis of the laser Doppler anemometry method, the spatial structure of a vortex turbulent flow, by means of an isothermal laboratory model of a vortex furnace of Central Design and Technology Institute, was studied.

Thus, devices with swirling flows become indispensable devices for the implementation of many technological processes found in various industries:

- in the production of a catalyst or adsorbent [8] – [10];

– in the oil industry, where hydrocyclones and separators are used to remove oil from associated water [11] – [13];

- when cooling or heating steam, steam condensation or boiling liquid.

However, the widespread introduction of devices with swirling vortex flows in the power industry is now being held back due to insufficient knowledge of the hydrodynamics of the vortex flow, as well as the processes of heat-mass transfer in the centrifugal field. Therefore, solving the problem of intensification of heat-mass transfer processes, collection and fractionation of particles, increase in the intensity of heat

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exchange by studying the behavior of the vortex structure are urgent tasks [14] – [16]. The simplest and most effective way to intensify heat transfer is to vortex the fluid medium flow in the annular channels of recuperative units [17] – [19]. In a vortex flow, centrifugal forces push the flow towards the wall of the apparatus, while a secondary transverse flow of the fluid medium occurs and an increase in the near-wall flow rate takes place, i.e. there is the summation of the longitudinal and transverse flow, which improves heat exchange [20].

II. STUDY OF THE VORTEX STRUCTURE IN A MULTI VORTEX DEVICE

The purpose of this scientific paper is to study the dependence of the change in the relative height of vortex formation on the dimension of the device structure by means of numerical simulation, as well as the dependence of the change in the relative height of vortex formation on the fluid medium flow rate. The height of the operating area is an important parameter, since the efficiency of the device depends on it. For example, the paper [21] shows the influence of the height of the liquid level on the efficiency of the proposed contact devices. The paper [22], [23] includes the studies of the influence of the geometrical dimensions of the device on the efficiency of the entire apparatus. In this paper, it is proposed to use a multi-vortex contact device with the holes arranged uniformly around the circumference at the lower end of the inner tube (Fig. 1).

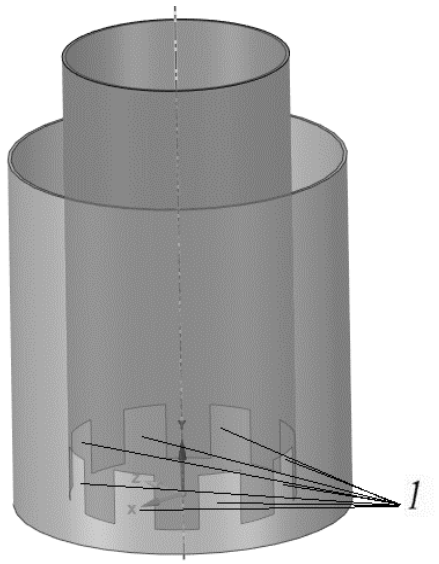

Fig. 1. 3D model of a multi-vortex contact device: 1 - holes arranged evenly around the circumference.

The device structure, shown in Figure 1, consists of two tubes and a bottom. Three device structures were studied, namely the inner diameter of the outer tube was 49, 98, 196 mm, and the outer diameter of the inner tube was 33.5, 67, 134 mm, respectively. The height of the outer tube was set to 356.25, 712.5, 142 mm, the height of the inner tube - 371.25, 742.5, 1485 mm. The thicknesses of the outer and inner tubes were set to 0.5 and 1, 2 mm. The height of the holes was 8, 16, 32 mm. Vortices were created in the space between the cylinders, therefore their diameters were 7.75, 15.5, 31 mm. The thickness of the bottom was 2 mm in all cases. There are 8 rectangular holes in the lower part of the inner tube, evenly arranged along the circumference.

ANSYS Fluent software package was chosen as a program for analyzing various mathematical models of turbulence. This software package is designed for modeling complex flows of liquids and gases with a wide range of changes in thermal properties by providing various modeling parameters and using the multigrid methods with improved convergence. The program uses the finite element method, which is a grid-based approach. Depending on the chosen turbulence model, the differential equations with partial derivatives are derived (the Navier-Stokes equation):

$$\frac{\partial \vec{v}}{\partial t} = -\left(\vec{v} \cdot \nabla\right)\vec{v} + \nu\Delta\vec{v} - \frac{1}{\rho}\nabla p + \vec{f} \quad (1)$$

Where ∇ – nabla; Δ – vector Laplace operator; t – time period, c; ν – kinematic viscosity coefficient, m^2/s; ρ – density, kg/m^3; p – pressure, Pa; $\vec{v}$ – velocity vector field; $\vec{f}$ – vector field of mass forces.

The Navier-Stokes equation is supplemented with the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho\vec{v}\right) = 0 \quad (2)$$

3D model of the flow around obstacle elements, and a structured uniform computational grid with the number of cells ~3638718, the number of nodes ~644553, is shown in Fig.2.

Fig. 2. Development of computational grid for a solid-state model of a multi-vortex contact device

The calculation was carried out in a stationary mode. The value of the water flow rate at the inlet of the calculated area was equal to 0,2, 0,5, 0,7, 1, 1,25, 1,5, 1,75, 2 m/s. The water temperature was set to 293 K. The value of the air flow rate at the inlet of the calculated area was equal to 1, 2, 5, 10, 15, 20, 25 m/s at a temperature of 293 K. At the outlet of the annular space, a pressure of 101325 Pa was set, and a temperature of 273 K was set for the walls as well. Numerical studies were carried out taking into account the energy equation. SST k-ω model with typical empirical coefficients, set by the program by default, was used in the course of numerical simulation. One of the advantages of k-ω model is the ability to more correctly describe the flow behavior in the near-wall area. Thus, simpler wall functions are used in this model than in k-ε models, providing better reliability and accuracy [24]. Water and air with physical properties, incorporated in the calculation complex, were used as operating media.

The solver (inference engine) used the "SIMPLE" algorithm with typical empirical coefficients set by the program by default. The choice of this method was due to the fact that the "SIMPLE" algorithm uses the relationship between rate and pressure corrections to ensure mass conservation and obtain a pressure field [25].

Experimental studies of changes in the relative height of vortices due to the flow rate in the device structures with vortex diameters of 7.75, 15.5, 31 mm were carried out. The experiments covered the range of changes in the Reynolds numbers from 3100 to 64000, calculated as per the rates under the study. In order to obtain reliable data, taking into account the grid margin of error, the experiments for each mode were repeated 4-6 times. During the experiments, the integrity of the vortex structures was investigated, the area of the beginning of the vortex structure destruction was determined. Figure 3 shows the beginning of the destruction of the 1st vortex in the structure.

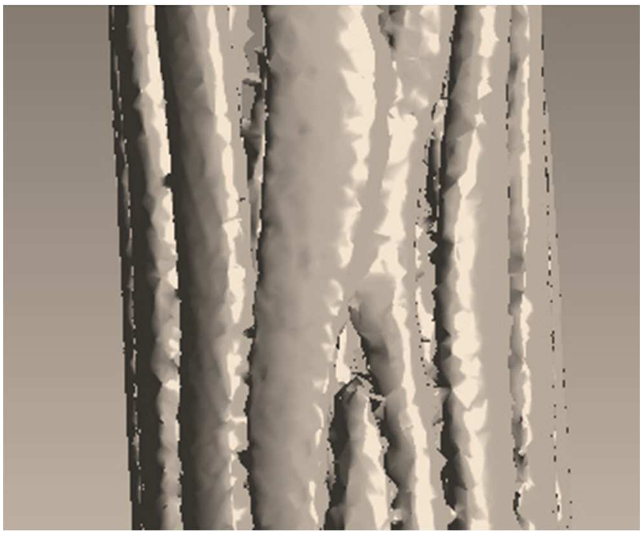

Fig. 3. Destruction of the vortex in water medium in the device structure with a vortex diameter of 7.75 mm and the hole height of 8 mm at the rate of 1.75.

III. RESULTS AND DISCUSSION

The results of the first series of experiments are shown in Figure 4. A range of values of the relative height of the vortices was obtained: from 7,74dv to 27,09dv mm. Analysis of the experimental data obtained showed that at high rates, a device structure with a vortex diameter equal to 31 mm has the highest relative height of the vortices. The quickest destruction of vortices takes place in the device structures with a vortex diameter of 15.5 mm. This nature of the change in the relative height of the vortices is explained by the increase in the disorder of the vortices, the formation of a hydrodynamic boundary layer, which is demolished by vortex structures. It should be noted that at low rates, higher values of the relative height of the vortices are observed.

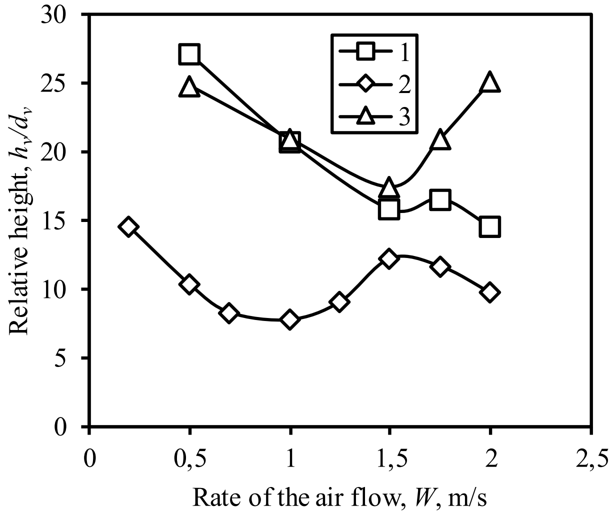

Fig. 4. The dependence of the relative height of the vortices in the device structures of different dimensions on the rate of the water flow with the vortex diameters d_v, mm: *1* – 7,75; *2* – 15,5; *3* – 31.

The further series of studies includes the results of comparing the dependence of the relative height of vortices on the air flow rate at the inlet of the device structures of different dimensions. The experiments were carried out with air rates at the inlet of the device within the range from 1 to 25 m/s. A range of values of the relative height of the vortices was obtained: from 11,35dv to 26,84dv. Figure 5 shows the dependence of the relative height of the vortices in the device structures of different dimensions on the air flow rate. Analysis of the experimental data obtained showed that at low rates the relative height of the vortex is higher than at high rates. It is worth noting that starting from 10 m/s, the relative height of vortices in all device structures, within the studied range, exceeds the value of 12dv, and at the rates of up to 2 m/s, the relative height exceeded the value of 20dv.

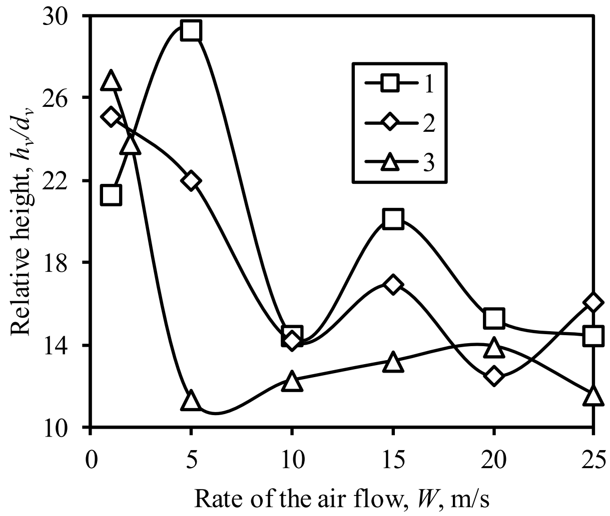

Fig. 5. The dependence of the relative height of the vortices in the device structures of different dimensions on the rate of the air flow with the vortex diameters d_v, mm: *1* – 7,75; *2* – 15,5; *3* – 31.

This nature of the change in the relative height of the vortices is due to the fact that at low rates the air flow is more orderly arranged, which mean that with an increase in the height of the operating zone, the vortices will retain the required structure longer.

In the final series of experiments, 2 device structures with the vortex diameters of 7.75 mm, but with different hole heights: 8 and 16 mm were compared. The aim of the experiment is to study the impact of changing the height of the hole on the relative height of the vortex. The experiments were carried out at water rates within the range from 0.5 to 2 m/s and at air flow rates within the range from 1 to 25 m/s. As a result of a series of experiments, the dependences of the relative height of the vortex on the water flow rate (Fig.6) and air flow rate (fig. 7) were obtained.

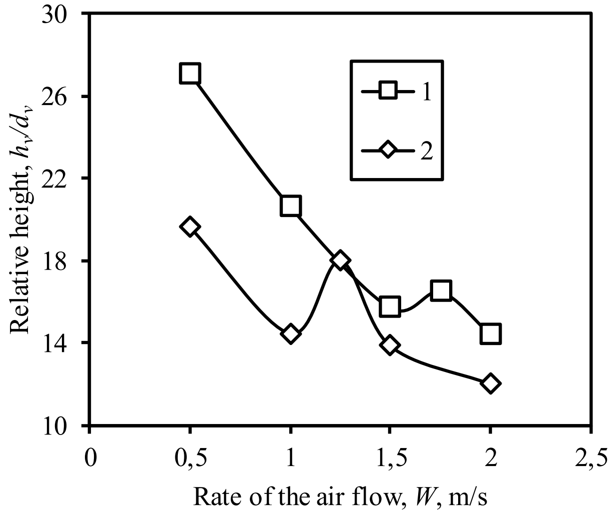

Fig. 6. The dependence of the relative height of the vortex in the device structures with a vortex diameter of 7.75 mm on the water flow rate at different heights of the holes: *1* - 8 mm, *2* - 16 mm.

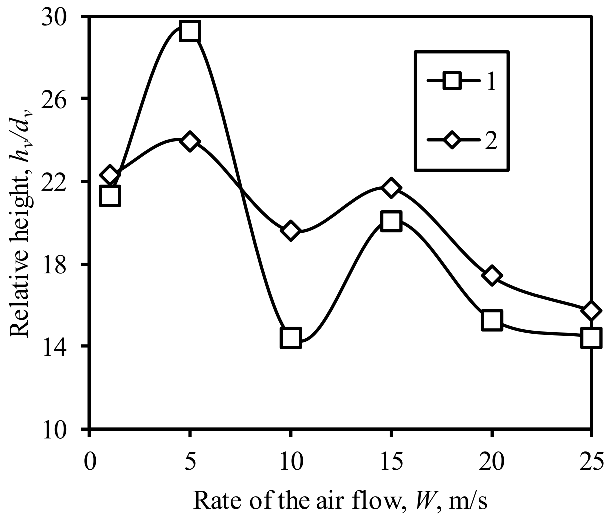

Fig. 7. The dependence of the relative height of the vortex in the device structures with a vortex diameter of 7.75 mm on the air flow rate at different heights of the holes: *1* - 8 mm, *2* - 16 mm.

Analysis of the experimental data obtained showed that the relative height of the vortex is on average higher in the device structure with a hole height of 8 mm, than in that one with a hole height of 16 mm. This is due to the fact that with an increase in the area of the hole, the flow passing rate decreases, that is, the values of the tangential rates of the vortex decreases, which means that the relative height of the vortex decreases as well. It can be concluded that the greater the angular rate of the vortices, the greater the relative height of the vortex, since the rate of the flow through the holes is approximately equal to the tangential rate at the periphery of the vortex.

IV. Conclusion

Considering the importance of the existing problem of increasing the efficiency of the processes of separation of heterogeneous systems and heat and mass transfer, a series of studies have been conducted in this paper to determine the influence of water and air flow velocities and geometric parameters of the proposed design on the relative height of vortex formation. As a result of a series of studies, it was found that at high water flow rates, vortices with a high relative height are created in the structure with a diameter of 31 mm, and with a diameter of vortices equal to 15.5 mm, numerical modeling showed that vortices are less stable and prone to instant destruction. It was found that at low air flow velocities, the relative height of the vortices is higher than at higher ones. This is due to the fact that at low speeds the air flow is more orderly, therefore, with an increase in the height of the structure, the vortices will maintain the required structure. It can be seen from the data obtained that the structure of the air flow vortices is more stable than the structure of the fluid flow vortices. In the final series of the study, 2 designs were compared, the height of the holes of which was excellent and equal to 8 and 16, respectively. The dependences of the relative height of the vortex on the velocity for the air flow and the fluid flow were obtained. Thus, we can conclude that at the flow rates, close to the operating ones, impact of them on the height of the vortices formed is minimal. An increase in the angular rate leads to an increase in the height of the vortices. The relative height of the vortices practically does not depend on their diameter.

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