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Numerical Simulation Of The Energy Separation Effect In The Ranke-Hilsch Tube

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Abstract – Currently, there are many applications of vortex technologies. The vortex effect is used in gas-dynamic cold generators and vortex refrigerating chambers. Vortex devices are also used as dehumidifiers, separators, for cooling and heating hydraulic fluids, separation of two-phase media, gas mixtures. Scientists are studying the applicability of vortex equipment for traditional and freeze-drying of agricultural products. However, the influence of the geometric parameters of vortex devices on the performance and energy efficiency of the temperature separation of gas flows has been poorly studied. Research aimed at finding opportunities and expanding the scope of application of vortex tubes is an urgent task. The article describes three-dimensional mathematical models of a swirling gas flow arising in a vortex tube. It presents the results of its implementation in the Comsol Multiphysics 5.6 software package. Thermodynamic and hydrodynamic characteristics confirm the effect of temperature separation in a vortex tube. The dependences of the temperature separation on the flow velocity at are obtained. For the three-dimensional vortex tube model, calculations were carried out using the turbulence model *v2-f*.

Keywords – Navier–Stokes equations, control volume method, SIMPLE method, QUICK scheme, Ranke-Hilsch tube.

I. INTRODUCTION

In the modern world, the use of the vortex effect to generate heat and cold is becoming more and more relevant [1, 2]. Vortex devices are used as a source of heat and cold for thermal effects and to improve the technical parameters of atomizers when dispersing various media [3-5]. The effect of temperature flow separation or vortex effect was discovered in 1931 by the French engineer Joseph Rank during experiments on industrial cyclones. He also developed a vortex tube design and received the first patent for the manufacture of a vortex tube. In 1946, the German scientist Robert Hirsch published the results of his experiments with vortex tubes, improving the design of the tube by J. The wound, and this phenomenon has become famous all over the world. R. Hilsh introduced classical criteria and values that are still used in calculations. Vortex tubes are named after their inventors – Rank tubes or Rank-Hilsch tubes [6, 7].

Vortex tubes have advantages such as simplicity of design, compactness; low production costs, high reliability; significant speed; implementation of several processes simultaneously: phase separation, cooling and heating of the gas stream [8, 9].The positive qualities of vortex devices make engineering systems technologically efficient, fast, easy to manufacture and operate, safe and environmentally friendly [10].

There are various types of vortex tube designs [11]. However, despite the relevance of the energy separation effect in various technological processes, there is no general theory of the vortex effect. This is due to the difficulty of studying the complexity of the flow in a vortex tube and significant turbulent pulsations [12, 13]. Therefore, the study of the Ranke-Hilsch effect and numerical modeling of the energy separation of the flow in a vortex tube remain urgent tasks.

II. Physical and mathematical formulation of the problem

Over many years of research, the main types of vortex tubes have been developed and classified: direct-flow, counter-flow, double-circuit and single-flow (with one flow) [14].

Consider the principle of energy separation in a countercurrent vortex tube (Fig. 1).Compressed air enters the vortex chamber and during the screw process, a free vortex is formed in the vortex tube, the temperature of which increases at the periphery and decreases in the center of the vortex. The heated gas exits through the energy separation chamber, and the cooled gas exits through the opposite end [15].

To conduct a numerical study, a classical design of a countercurrent vortex tube with certain geometric parameters was developed (Fig. 2). It consists of a vortex chamber 1 (vortex) with tangential compressed air supply, a hole for cold gas outlet 2 and a hole for hot gas outlet 3 and an energy separation chamber 4, which is a hollow pipe.

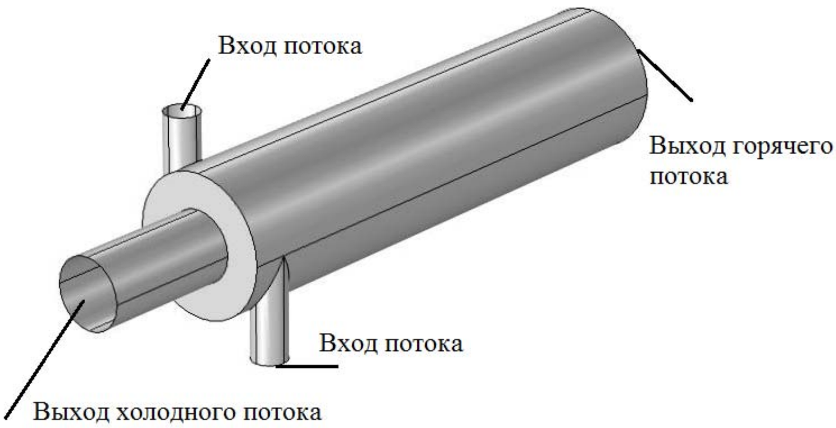


Fig. 1. Technological scheme of energy separation in a vortex tube

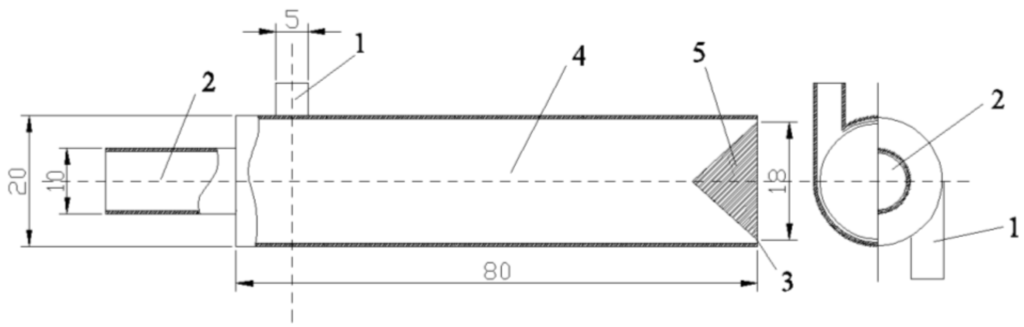


Fig. 2. Geometric area of the vortex tube: 1 – vortex chamber; 2 – hole for cold gas outlet; 3 – hole for hot gas outlet; 4 – energy separation chamber; 5 – choke.

The aim of the study is to study the Ranke-Hilsch effect and simulation of temperature flow separation in a vortex tube based on the Comsol Multiphysics 5.6 software package.

Numerical simulation of the energy separation effect in a vortex tube was carried out in three-dimensional approximations. When modeling the energy separation process in a vortex tube, the following assumptions were made [16, 17]:

1) The model of gas flow in a vortex tube is stationary, turbulent and swirling;

2) A compressible viscous ideal gas is considered as a medium.

For the mathematical description of a three - dimensional gas flow , the following equations were obtained ::

1) The continuity equation:

$$\frac{\partial \rho \bar{U}_i}{\partial x_j} = 0 \tag{1}$$

2) The equation for momentum:

$$\rho \frac{\partial \bar{U}_i}{\partial t} + \rho \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial p}{\partial x_j} = \mu \frac{\partial^2 \bar{U}_i}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j}\left(-\rho \overline{v_i' u_j'}\right). \tag{2}$$

3) Temperature distribution equation:

$$C_p \frac{\partial \rho T}{\partial t} + C_p \bar{U}_j \frac{\partial \rho T}{\partial x_j} = \lambda \frac{\partial^2 T}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j}\left(-\rho C_p \overline{T' u_j'}\right). \tag{3}$$

v2-f turbulence model: Near solid walls, the intensity of velocity fluctuations in the direction tangential to the wall is usually much higher than the intensity of fluctuations in the direction normal to the wall. In other words, velocity fluctuations are characterized by anisotropy. As you move away from the wall, the intensity of fluctuations in all directions becomes the same. The velocity fluctuations become homogeneous or isotropic. The anisotropy of turbulent fluctuations in the boundary layer is described by the v2-f turbulence model by introducing two additional equations solved together with the equations for the kinetic energy of turbulence (k) and the kinetic energy dissipation rate (ε).

$$\begin{cases} \rho \frac{\partial k}{\partial t} + \rho \bar{U}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho\left(v + \frac{v_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) + \rho P - \rho \varepsilon, \\ \rho \frac{\partial \varepsilon}{\partial t} + \rho \bar{U}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho\left(v + \frac{v_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right) + \frac{\rho}{\tau}\left(C'_{\varepsilon 1}(\zeta, \alpha) P_k - C'_{\varepsilon 2}(k, \varepsilon, \alpha)\varepsilon\right), \\ \rho \frac{\partial \zeta}{\partial t} + \rho \bar{U}_j \frac{\partial \zeta}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho\left(v + \frac{v_t}{\sigma_\zeta}\right)\frac{\partial \zeta}{\partial x_j}\right) + \frac{2\rho}{k}\left[\alpha^3 v + \frac{v_t}{\sigma_\zeta}\right]\frac{\partial k}{\partial x_j}\frac{\partial \zeta}{\partial x_j} + \rho\left(1 - \alpha^3\right) f_w + \rho \alpha^3 f_h - \rho \frac{\zeta}{k} P_k. \end{cases} \tag{4}$$

The turbulent vortex viscosity is calculated by: $v_t = C_\mu k \zeta \tau$.

When developing a mathematical three-dimensional model, the following boundary conditions were set: At the entrance to the vortex tube, the total pressure $P = P_1$.

At the outlet of the vortex tube, the static pressure is equal to atmospheric pressure, and the radial pressure distribution is equal to

$$\frac{\partial P}{\partial r} = \frac{\rho w^2}{r}. \tag{5}$$

III. SOLUTION METHOD

The system of equations was solved by the finite volume method. A second-order accuracy scheme was used to determine gas-dynamic flows and approximate convective flows in cells [18-25].

The system of equations was solved using the finite volume method. To determine gas-dynamic flows and approximate convective flows in cells, a second-order accuracy scheme was applied using the QUICK method [25-29]. The problem was solved using the Comsol Multiphysics 5.6 software package. This numerical simulation includes the following steps:

IV. CALCULATION RESULTS AND THEIR DISCUSSION

By the method described above, studies were carried out and the results of numerical simulation of the energy separation of the vortex flow in three-dimensional approximations were obtained. The studies were carried out at the following inlet flow rates – U = 50-300 m/s. Figure 3 shows the change in outlet temperature when the flow rate changes.

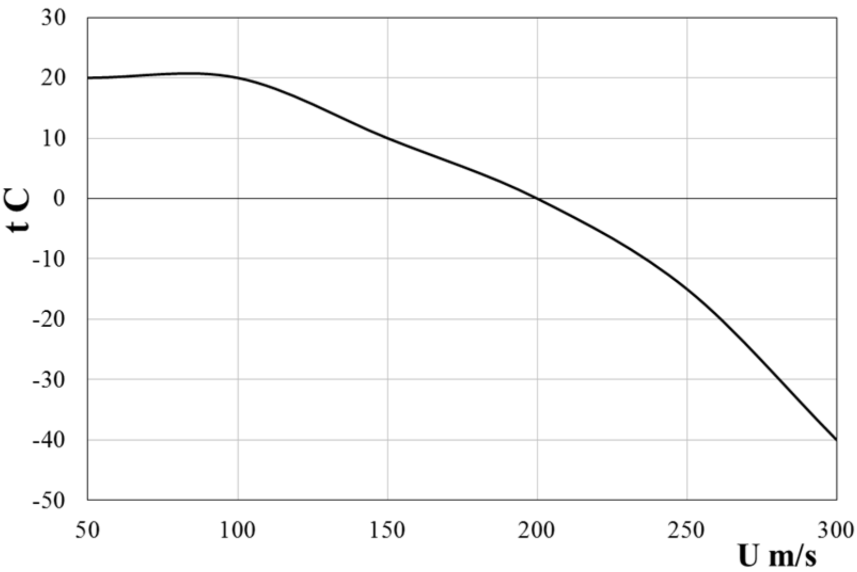
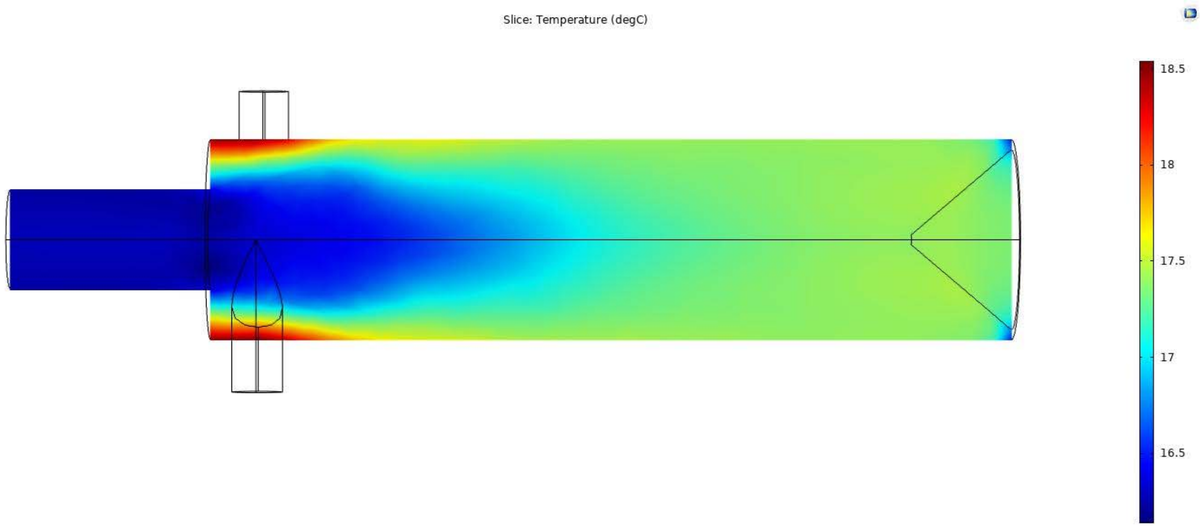
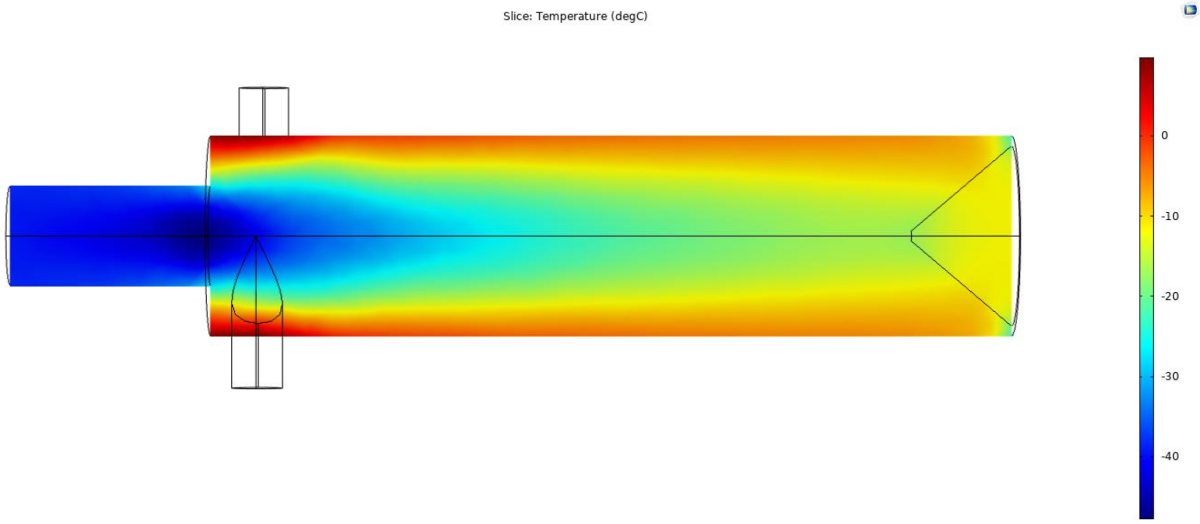


Fig. 3. Change in outlet temperature when the flow rate changes

Figure 4 shows the temperature distribution.

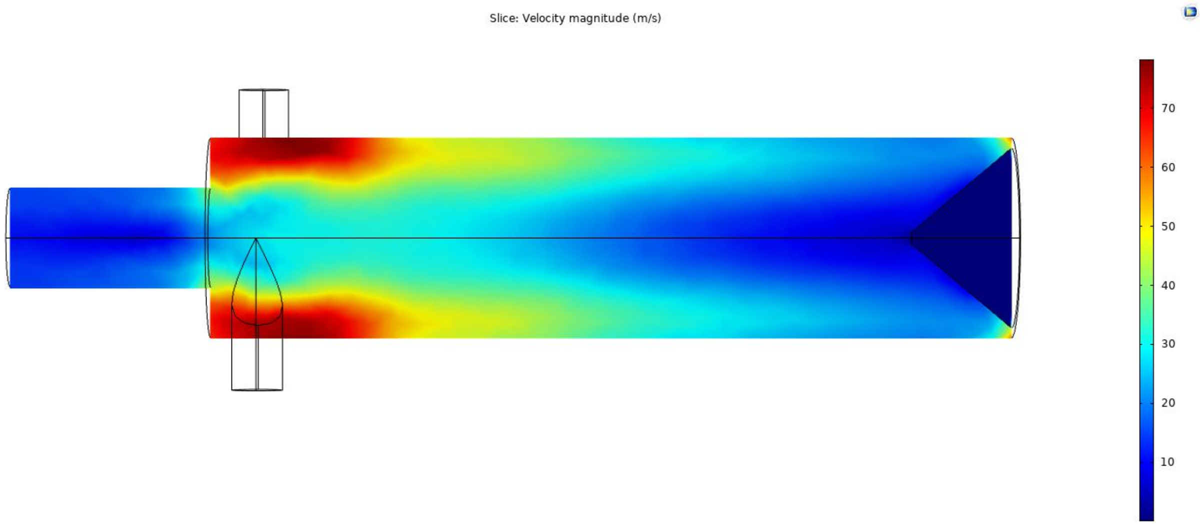


U = 50 м/с

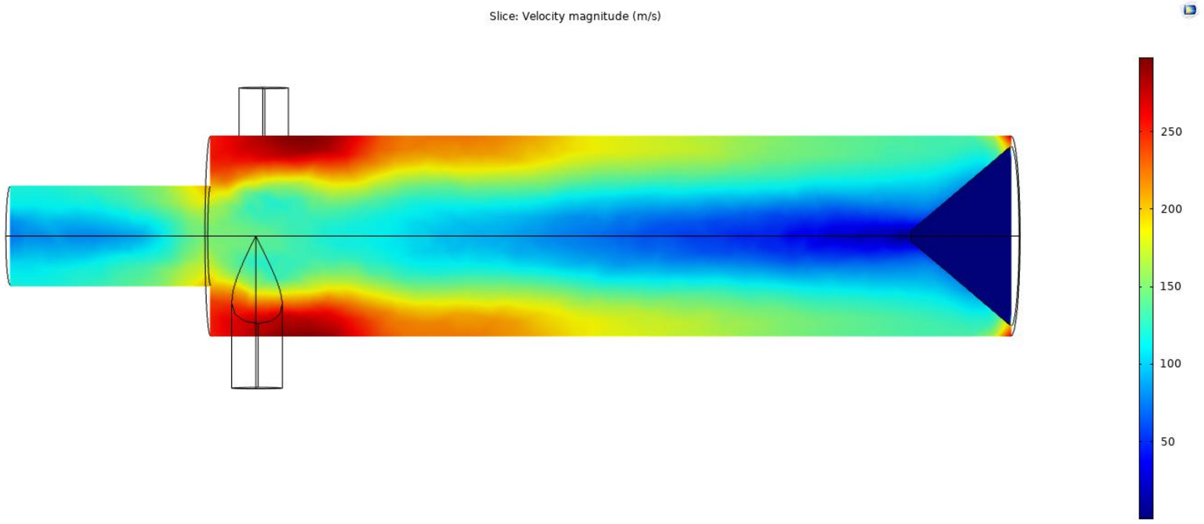


U = 300 м/с

Fig. 4. Temperature distribution



U = 50 м/с



U = 300 м/с

Fig. 5. Speed distribution

From the general temperature field (Fig. 4), it can be observed that the temperature increase occurs in the wall area at the outlet. At the same time , there is a noticeable decrease in temperature in the central part . It is 20 to -40 C.

V. Conclusions.

Numerical simulation of the three-dimensional flow of a gas stream in a Rank-Hilsch vortex tube is carried out. Thermodynamic and hydrodynamic characteristics confirming the effect of temperature separation of the flow are obtained. The influence of the flow velocity on the temperature separation was investigated. Vortex devices remain an actual subject of research for many scientists. Knowledge of the processes occurring in vortex tubes will allow us to create a more accurate mathematical model that will increase the energy efficiency of installations and will allow us to evaluate new devices at the design stage and expand their scope of application in technological processes.

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