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NUMERICAL RESEARCH OF THE MODIFIED TAYLOR FLOW . DEVELOPMENT OF THE NEW CONCEPT OF THE INDUSTRIAL MIXER.

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Abstract

In the article the results of numerical researches of laminar fluid flow , evolution of the passive impurity and small solid particles in modified Taylor flow are presented. Fluid medium moves between undulating surfaces of rotor and fixed body. The dependence of flow field against Reynolds number and geometrical parameters of rotor and body surfaces is explored. The possibility of using similar kind flows in industrial devices for mixing, suspending and emulsifying is considered.

Introduction.

An idea of Taylor flow usage for the effective solution of problems of mixing, suspending and emulsifying in the industry is not new. For example in the article [1] the Couette-Taylor flow is proposed for extracting residuals of uranium and plutonium from spent nuclear fuel. Such a mixer consists of a cylindrical body with an inner radius R_2 and cylindrical rotor of radius R_1. Mixing is realized in the gap a=R2-R1, in a system of Taylor cells approximately periodic along the axis of rotation (z).

However similar devices not always appear effective. Their main imperfection, according to our opinion, is the strong effect of a radial separation of the mixture components having different density. Because of it in the mixer design it is necessary to use a small radial gap $a \leq 0.1R_2$. That results in essential decreasing of working volume of the mixer, large drag torque and high power inputs per unit volume of mixed medium. Besides the longitudinal size (period λ) of vortical structures becomes very small ($\lambda \approx 2$?), that impedes exchange of mass, momentum and energy between different parts of working volume.

In the given article, for mixing it is offered to use the modified Taylor flow between undulating (axisymmetrical and periodic along rotation axis z) surfaces of a rotor and fixed body. The fact of existence of such flows, caused by a undulating surface of rotor at a cylindrical surface of a body ($R_1(z)=A+B\cos(kz)$, $R_2(z)=R=const$) is established and experimentally verified in [2]. But at a cylindrical surface of a body it fails to decide a problem of effective counteraction to the phenomenon of radial separation of the mixture components having different density.

Research object and numerical methods.

The effective solution of mixing problems is supposed to achieve using a new method of organizing the flow of medium to be mixed. The specific features of this method, realized in several variants of the mixer design, are as follows (fig.-1):

- Mixing is realized in a system of cells, periodic along the axis of rotation (z), formed by shapes of the rotor $R_1(z)$ and the body R_2 (z) surfaces, periodic along z. When the rotor rotates, toroidal vortex structures occur in this system caused by shapes of surfaces $R_1(z)$ and $R_2(z)$, their period λ is determined by the period of changing the radii of the rotor and the body.
- The surfaces of the rotor $R_1(z)$ and the body $R_2(z)$ are not cylindrical, they belong to a class of continuous functions with a limited first derivative with respect to z and satisfy the inequality: $0<R_1(z)< R_2(z)\leq R$, the presence of both rotor surface bulges (maxima of function $R_1(z)$) and body surface bulges (minima of function $R_2(z)$) being necessary.
- Non zero, integral on cross section of the mixer, flow rate develops along the z-axis. Its mean velocity is much less than the characteristic velocity of circumferential flow.

Thus, fluid medium is actuated at the expense of shearing stresses arising on the rotor surface, enough uniformly distributed in all volume and terminated on the body. Such a macroscopic flow organization with large periodic vortical structures, connected by common axial flow, provides a uniform distribution of immixed components in the mixer volume and effective exchange of mass and heat between different areas (including processes of dissolution of an impurity and chemical reactions).

In the work the numerical modeling of fluid flow and evolution of an impurity concentration in the mixer of the simplified geometry is held. The mathematical model of fluid flow is constructed within the framework of axisymmetrical non-stationary Navier-Stokes equations. A liquid - incompressible, its viscosity, heat conduction and diffusion coefficient are constant, on left-hand and right (on the axis z) boundaries the requirements of periodicity are put. The presence of an impurity does not influence flow of liquid and its properties (completely passive impurity).

For evolution of the passive impurity concentration the special mathematical model with known flow field of the liquid is constructed. It is the three dimension non-stationary equation of transferring and diffusion of the passive impurity (temperature).

To study the efficiency of counteraction from the separation phenomenon of the mixture components having different density, the evolution of an ensemble of small solid particles in flow field of the liquid is numerically investigated. The motion of particles is considered within the framework of Tchen model [3] - taking into account the Stokes force, forces of a gravitation, buoyancy and pressure gradient in a liquid, but disregarding the Busse forces.

For the estimation of influencing of small random disturbances on particles dynamics, the simplified model of Brownian motion is added to equations of motion. The limit distribution of probability density of particles location in the mixer volume is calculated.

Results.

Main parameters of the problem are Reynolds number $Re = \frac{\rho\omega R^2}{\mu}$, where R maximum radius of an internal surface of a body, μ, ρ - viscosity and density of liquid medium, ω - angular rate of rotor rotation, diffusive Prandtl number Pr, period λ and normalized on R the functions $R_1(z)$, $R_2(z)$, which determine the shapes of undulating surfaces of rotor and body.

With the aid of calculations the flow patterns of a liquid are analyzed and the parameters ensuring the greatest intensity of radial-axial fluid flow and creation intensive and uniform on volume transfer of mass, momentum and heat are determined.

For example, on fig. 1 the streamlines in the (r,z) plane for variant-1 of geometrical shape of the mixer cell are shown.

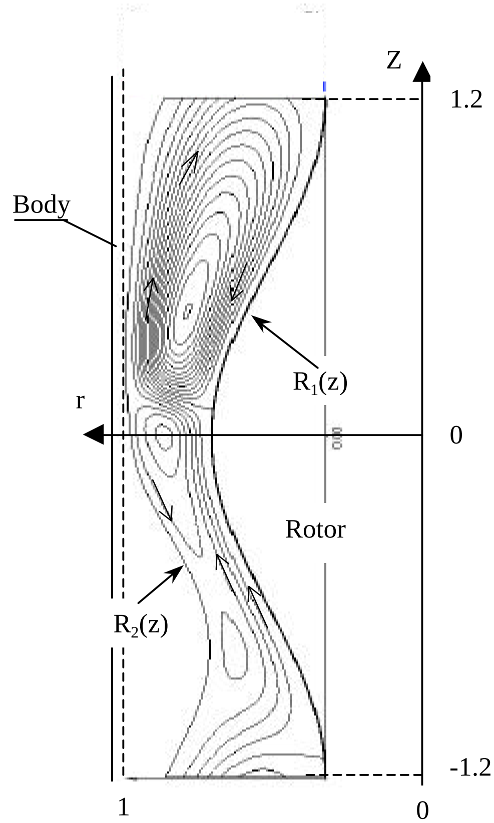

Fig. 1: Streamlines in the (r, z) plane, calculation at Re=500 , λ=2.4 .

The phenomenon of non zero, integral on cross section of the mixer, flow rate along the axis z is obtained by the calculations. And the demanded axial flow rate forms without an external pressure gradient. The nature of this hydrodynamic effect is established: The asymmetrical shape of the rotor R_1 (z) and body R_2 (z) surfaces results in asymmetrical pressure distribution on these body surface and appearance of non zero net force along the axis z. It causes the axial flow rate.

For the estimation of mixing efficiency on quantitative and qualitative characteristics, the matching with the existing prototype - Taylor vortexes mixer is carried out. It is shown, that in the new mixer the given level of homogeneity of impurity distribution is reached at 2-4 times smaller costs of energy per unit volume.

On fig. 2 the diagram of time evolution of maximum deviation of impurity concentration Cm from the mean volume concentration Ca are presented. The calculations are made at Re=500 , Pr=5 for the Taylor mixer R_1=0.64, R_2=1 (1) and for the mixer of new geometrical shape (2) (fig. 1).

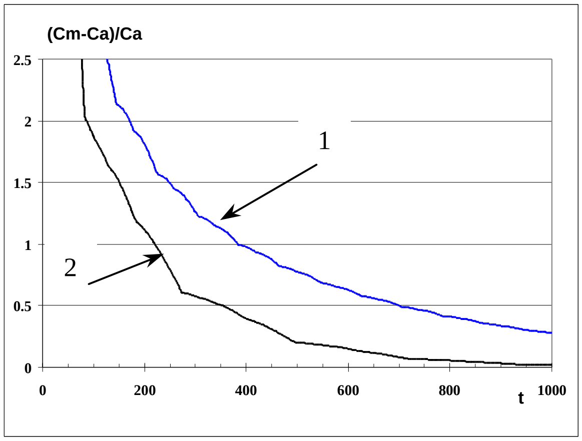

Fig. 2: Time evolution of maximum deviation of impurity concentration Cm from the mean volume concentration Ca. Re=500, Pr=5.

Relative density ρ_p/ρ and relative diameter d/R of particles are parameters in a problem about motion of particles.

By means of numerical modeling of small solid particles motion in the flow field of a liquid it is established, that the undulating internal surface of a body gives approximately 2 times reduction of particles concentration excess at the wall of a body.

On fig. 3 the chart of a limit distribution of probability density of particles location on the radial coordinate is presented. An abscissa axis is the relative distance $Y=(r-R_1)/(R_2-R_1)$ from a surface of the rotor, where Y=0 corresponds to the rotor surface and Y=1 corresponds to the surface of the mixer body.

The calculations are made at $\rho_p/\rho=3$, d/R=0.01 for the mixer with a cylindrical internal surface of a body $R_2=1$ (1) and mixer of the new geometrical form (2) (fig.1).

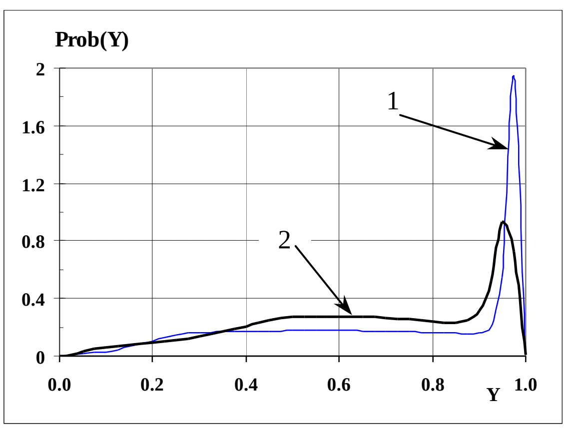

Fig. 3: Limit distribution of probability density of particles location on the radial coordinate

$Y=(r-R_1)/(R_2-R_1)$.

Conclusions.

The analysis of introduced results demonstrates, that the undulating surfaces of a rotor and body are the strong forcing factor resulting in to formation of toroidal vortical structures with a given period on rotation axis. As a result of a special selection of surface shapes for the rotor and the body it is possible to organize the forced vortex flow with the intensity much exceeding that of the Taylor vortices at the same power consumption. In addition, the proposed shape of the internal mixer cell volume makes it possible to significantly overcome the effect of separation of mixture components having different density

The numerical modeling of time evolution of the passive impurity concentration and motions of an ensemble of small solid particles in the flow field of liquid has confirmed an optimization capability of the rotor and body shapes for the effective solution of mixing, suspending and emulsifying problems in the industry .

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