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A. P. Khomyakov, S. V. Mordanov, D. R. Naskina, et al.



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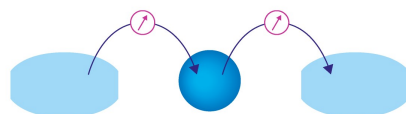
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Investigation of the Hydrodynamics of Mixing Two Technological Media with a Small-Sized Agitator

A. P. Khomyakov, S. V. Mordanov, D. R. Naskina^{a)} and T. V. Khomyakova

Ural Federal University, 19, Mira str., 620002, Yekaterinburg, Russia.

^{a)}Corresponding author: dilay1909@mail.ru

Abstract. The paper shows the results of the two-phase mixing hydrodynamics simulation in the first reactor of the crystallization cascade. The research results were obtained using the ANSYS Fluent CFD code. The distributions of velocity and liquid mixture components volume fractions were obtained. The time of the full averaging of the liquid mixture components volume fractions were obtained.

INTRODUCTUION

The technological process of ammonium polyuranate deposition is realized by mixing solutions of the uranyl sulfate and the ammonium carbonate salt solutions. The uranium precipitation from the dilute sulfuric acid solutions depends on several factors, one of which is the distribution evenness of fluids in the apparatus volume. In the current installation of the deposition process, the cascade consisting of three series-connected reactors with the mixing device and the heat exchanger in each is used.

The numerical simulation of the mixing hydrodynamics was carried out using ANSYS Fluent CFD code with standard k-epsilon turbulence model and Mixture model. The two-phase model with technological media of various densities was considered in the research.

NUMERICAL SIMULATION

The mathematical model based on Navier-Stokes equations and standard k-epsilon turbulence model was used for CFD simulation. For steady-state isothermal conditions Navier-Stokes equations takes form [1]:

$$\operatorname{div}(p\vec{u}) = 0 \quad (1)$$

$$(pu_j) \frac{\partial u_i}{\partial x_j} = \frac{dp}{dx_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] + \rho g_i \quad (2)$$

There ρ is the density, kg/m³; u is the velocity, m/s; i, j are the indexes of the longitudinal and the transverse directions of the flow; x is the coordinate, m; p is the pressure, Pa; μ is the viscosity, Pa·s; δ_{ij} is the metric tensor; g is the gravity force acceleration, m/s².

Standard k-epsilon turbulence model [2, 3] for the steady-state isothermal conditions takes form:

$$\frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \epsilon \quad (3)$$

$$\frac{\partial}{\partial x_i} (\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} G_k - C_{2\epsilon} \rho \frac{\epsilon^2}{k} \quad (4)$$

$$G_k = \mu_t S^2 \quad (5)$$

$$S \equiv (2S_{ij}S_{ij})^{0.5} \quad (6)$$

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \quad (7)$$

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (8)$$

There k is the specific turbulent kinetic energy, J/kg; μ_t is the turbulent viscosity, Pa·s; G_k is the turbulent kinetic energy generation due to the average flow gradient, J/(m³·s); ε is the specific turbulent kinetic energy dissipation, J/(kg·s); S is the viscous stress tensor module, s⁻¹; S_{ij} is the viscous stress tensor, s⁻¹. The values of the model constants were taken according to Marshall and Bakker [4]: $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, $C_\mu = 0.09$.

In our research we used Manninen and coworkers Mixture model [5] to simulate the liquid mixture components volume fractions averaging processes. According this model, the mass and momentum conservation equations take form:

Continuity equation for the mixture:

$$\frac{\partial}{\partial t}(\rho_m) + \text{div}(\rho_m \mathbf{u}_m) = 0 \quad (9)$$

$$\begin{aligned} \frac{\partial}{\partial t}(\rho_m u_{m_i}) + \left[(\rho_m u_{m_j}) \frac{\partial u_{m_i}}{\partial x_j} - \sum_{\varphi=1}^n (\alpha_\varphi \rho_\varphi u_{dr_j \varphi}) \frac{\partial u_{dr_i \varphi}}{\partial x_j} \right] = \\ = - \frac{dp}{dx_i} + \frac{\partial}{\partial x_j} \left[\mu_m \left(\frac{\partial u_{m_j}}{\partial x_i} + \frac{\partial u_{m_i}}{\partial x_j} - \frac{2}{3} \delta_{ij} \frac{\partial u_{m_i}}{\partial x_i} \right) \right] + \rho_m g_i \end{aligned} \quad (10)$$

$$\rho_m = \sum_{\varphi=1}^n \alpha_\varphi \rho_\varphi \quad (11)$$

$$\mathbf{u}_m = \frac{\sum_{\varphi=1}^n \alpha_\varphi \rho_\varphi \mathbf{u}_\varphi}{\rho_m} \quad (12)$$

$$u_{dr \varphi i} = u_{\varphi i} - u_{m_i} \quad (13)$$

$$\mu_m = \sum_{\varphi=1}^n \alpha_\varphi \mu_\varphi \quad (14)$$

There m is the index of the mixture parameters; φ is the index of the phase parameters; u_{dr} is the phase drift speed, m/s.

RESULTS AND DISCUSSION

Studies of the phases volume fractions distribution and flow rates were carried out for the reactor with a 16 m³ volume, which overall dimensions were: diameter 2400 mm, the cylindrical part height 3500 mm. This reactor has a 400 mm diameter six-blade mixing device and a heat exchanger. The calculations were carried out without considering heat exchange equipment operation, but with the heat exchanger design influence on the mixing process. Research was performed for the mixing device stirring speed (n) 420, 720 and 1020 rpm. The operating mode of the device is accepted to be periodic.

Figure 1 shows the distribution of flow velocities for the considered rotating mixing device rotation speed. It is found that the distribution of flow rates is uneven. For the rotation speed of 420 rpm the velocity ranges from 0 to 8,5 m/s, for the rotation speed of 720 rpm the velocity ranges from 0 to 14,6 m/s, for the rotation speed of 1020 rpm the velocity ranges from 0 to 20,7 m/s. The maximum velocity value is observed near the mixer blades for all mixer operating regimes. The low velocity values prevail in the device volume.

The simulation results show that for the observed range of the mixer rotation speed the velocities distribution does not depend on the rotor speed qualitatively. The velocities flow distribution is formed by the vortices located near the

mixer blades and in the reactor center-bottom part inside the heat exchanger coil. Outside the heat exchanger coil, the velocities flow distribution is formed by axial flows. Thus, the heat exchanger coil acts on the flow in the reactor volume like a central circuit tube. The absolute values of the flow velocities throughout the reactor (especially near the mixer) increase with the mixer rotation speed growth.

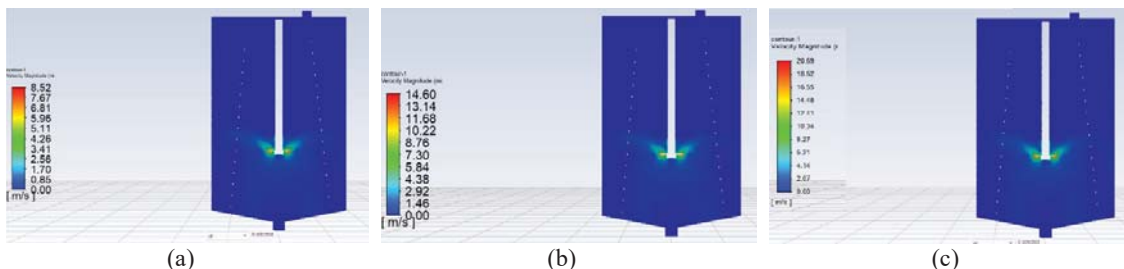


FIGURE 1. Velocities distribution in the reactor at (a) 420 rpm. (b) 720 rpm. (c) 1020 rpm

Volume fractions distribution data were also obtained for the device. Figure 2 shows the solutions distribution of uranyl sulfate and carbon ammonium salt at the initial time.

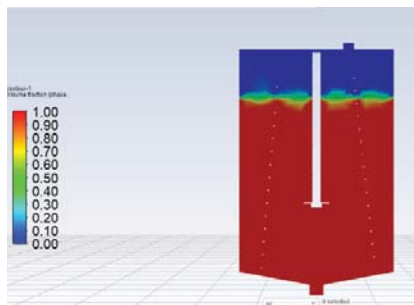


FIGURE 2. Volume fraction distributions of solution at the initial time

Volume fraction distributions of uranyl sulfate solution at the rotation speed of 420,720,1020 rpm, after 15 minutes of the mixing device are shown on Figure 3. The minimum values of the uranyl sulfate solution volume fraction are: 0,39 for the rotation speed of 420 rpm, 0,72 for the rotation speed of 720 rpm, 0,84 for the rotation speed of 1020 rpm.

Figure 4 presents data on volume fraction distribution of the solution after 30 of the mixing. It is shown that the velocity increasing provides the more even flow distribution.

Figures 5 and 6 shows that the even distribution of the solutions volume fractions in the reactor volume stabilize after 45 minutes of the mixing for the rotation speed of 720 rpm and 1020 rpm; and after 60 minutes for the rotation speed of 420 rpm.

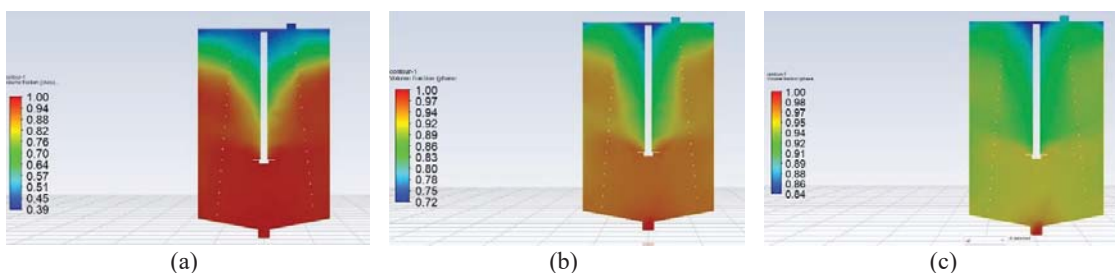


FIGURE 3. Volume fraction distribution of the uranyl sulfate solution at a) $n=420$ rpm b) $n=720$ rpm c) $n=1020$ rpm, after 15 minutes of the mixing

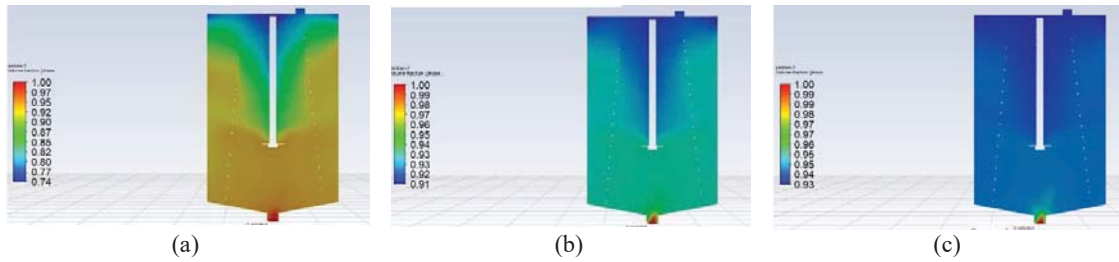


FIGURE 4. Volume fraction distribution of the uranyl sulfate solution at a) $n = 420$ rpm b) $n = 720$ rpm c) $n = 1020$ rpm, after 30 minutes of the mixing

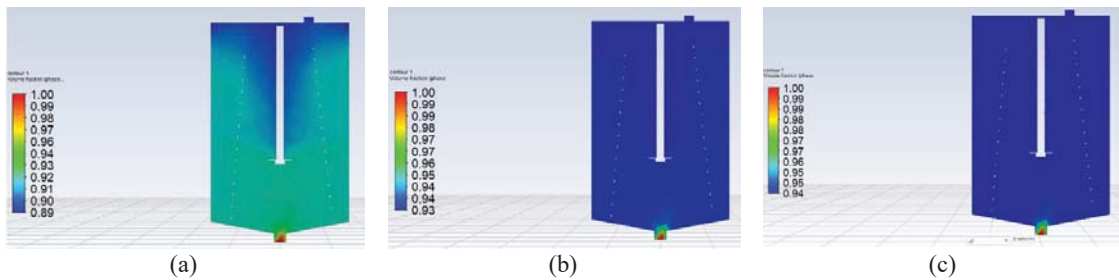


FIGURE 5. Volume fraction distribution of the uranyl sulfate solution of a) $n = 420$ rpm b) $n = 720$ rpm c) $n = 1020$ rpm, after 45 minutes of the mixing

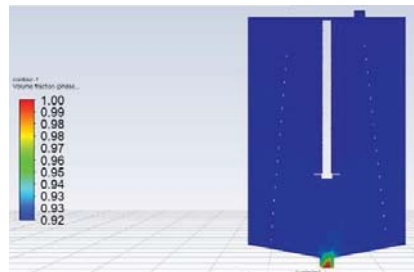


FIGURE 6. Volume fraction distribution of the uranyl sulfate solution of at $n = 420$ rpm after 60 minutes of the mixing

Table shows the numerical indicators of the flow rates and time that is required to establish an even distribution of the phases at the mixing device different rotational speed. The mixing device rotational speed changes does not significantly affect the average flow rate in the device and, due to the small agitator size, it shows only local increases in the flow velocity near the mixing device blades.

TABLE 1. Flow rates numerical indicators and time required to establish an even phase distribution

Mixer operation mode (n)	Flow rate, m/s			Time required for even distribution, min
	Minimal	Average	Maximal	
420 rpm	0,01	< 1	8,52	60
720 rpm	0,01	< 1,5	14,60	45
1020rpm	0,01	< 2	20,69	45

CONCLUSIONS

The simulation of two solutions mixing in batch mode reactor was carried out. Also, we revealed the heterogeneity of the phase distribution under mixing device certain operating conditions. For an even phase distribution in the reactor volume there were requires: at least 45 minutes of mixing for the mixer speed of 720 and 1020 rpm and at least 60 minutes of mixing device operation for the mixer speed of 420 rpm, provided that the operating mode is periodic.

The distribution of the flow velocities in the reactor volume is uneven. The low flow velocities are mostly observed. The uneven fluid distribution in the volume of the device may lead to the lower deposition rates. More intensive mixing promotes the better contact of the solutions and increases the deposition efficiency.

It was found that for an even distribution of the process media in the device volume, it is necessary to change the design of the mixing device.

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