Investigation of the mixing hydrodynamics of two-component solution with the three-blade agitator

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Abstract. The studies were performed using Ansys Fluent software. The Manninen’s multi-phase model and the standard k-epsilon turbulence model were employed for numerical calculations of hydrodynamics; the non-continuous operating mode of a reactor was adopted. A three-blade agitator was used for mixing of the two process media. In the current study, a numerical simulation of the hydrodynamics was carried out under various operating modes of the mixing device. The data on the volume fractions distribution of process media and the speed distribution of flows in the reactor have been obtained and analysed.

1. Introduction
The precipitation process of ammonium polyuranate from dilute sulfuric acid solutions by mixing with an ammonium carbonate solution is realized in reactors of volume 16 m³, equipped with a heat exchanger and a mixing device.

The previous studies of mixing hydrodynamics in a reactor equipped with a six-blade mixing device (Fig. 1a) showed the presence of stagnant zones and a long residence time of particles in the reactor [1]. It can be assumed that more uniform distribution of the ammonium carbonate solution in the reactor volume will reduce the consumption of the reagent as well as will lead to a decrease in the residence time of the solution in the reactor. Therefore, the hydrodynamics of mixing with a three-blade agitator was investigated (Fig. 1b).

Figure 1. a) Real agitator; b) three-blade agitator.
This paper presents the study of hydrodynamics of the two-process media mixing with a three-blade agitator. The studies were carried out by the numerical simulation method.

2. Methods
The mathematical model based on Navier-Stokes equations and standard k-epsilon turbulence model was used for pump CFD simulation. For steady-state isothermal conditions, Navier-Stokes equations takes form [2]:

\[
\text{div}(\rho \mathbf{u}) = 0
\]
\[
(p \mathbf{u}_j) \frac{\partial u_i}{\partial x_j} = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right] + \rho g_i
\]

where \( \rho \) is the density, kg/m\(^3\); \( u \) is the velocity, m/s; \( i, j \) are the indices of the longitudinal and the transverse directions of the flow; \( x \) is the coordinate, m; \( p \) is the pressure, Pa; \( \mu \) is the viscosity, Pa·s; \( \delta_{ij} \) is the metric tensor; \( g \) is the gravity force acceleration, m/s\(^2\).

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

\[
\frac{\partial}{\partial x_i} (p k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon
\]
\[
\frac{\partial}{\partial x_i} (p \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}
\]
\[
G_k = \mu_t S^2
\]
\[
S = (2S_{ij} S_{ij})^{0.5}
\]
\[
S_{ij} = \frac{1}{2} \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right)
\]
\[
\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}
\]

where \( k \) is the specific turbulent kinetic energy, J/kg; \( \mu_t \) is the turbulent viscosity, Pa·s; \( G_k \) is the turbulent kinetic energy generation due to the average flow gradient, J/(m\(^3\)·s); \( \varepsilon \) 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]: \( C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92, \sigma_k = 1.0, \sigma_\varepsilon = 1.3, C_{\mu} = 0.09 \).

3. Results
The studies were performed under the following conditions:

1) the diameter of the reactor was 2400 mm and the height of cylindrical part was 3500 mm;
2) the three-blade agitator with diameter of 1000 mm was used for mixing;
3) the non-continuous mode of operation was adopted;
4) the frequency of rotation of the mixing device was 420, 600, 720, and 1020 rpm;
5) the ammonium carbonate solution density and the diluted sulfuric acid solution density were 1130 kg/m\(^3\) and 1200 kg/m\(^3\), respectively;
6) the volume ratio of the liquids (ammonium carbonate solution and diluted sulfuric acid solution) was 1:5.

Figure 1b shows a 3D model of apparatus equipped with the three-blade mixing device.
In this study, the values of process media speeds in the volume of the reactor were defined at different operating modes of the three-blade agitator (Fig. 2). In all cases, the maximum speed is observed directly near the blades. The nature of the distribution of flow speeds is similar for all considered operating modes of the mixing device. The average flow velocity in the reactor volume changes from 2.5 to 6 m/s being 2.5 m/s at 420 rpm, 3.5 m/s at 600 rpm, 4.4 m/s at 720 rpm, and 6 m/s at 1020 rpm.

Figure 2. The velocity distribution of flows at: a) 420 rpm, b) 600 rpm, c) 720 rpm, and d) 1020 rpm in the reactor volume.

Figure 3. Distribution of the technological medium 1, in the reactor after 15 minutes of operation of the agitator at: a) 420 rpm, b) 600 rpm, c) 720 rpm, and d) 1020 rpm.
As an example, the distribution of fluids at the initial time and in 15 minutes under various operating modes are shown in Figure 3.

The Table 1 contains data on flow speed and minimum residence time of process media necessary to achieve a uniform distribution throughout the reactor. Dependence of the maximum flow speed on the rotational speed of the mixing device has been determined and given below:

$$V = 0.02 \times n$$

where $V$ - the maximum speed, m/s; $n$ - the rotational speed of mixing device, rpm.

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

| Mixer operation mode | Flow rate, m/s | Time required for even distribution, min |
|----------------------|----------------|------------------------------------------|
|                      | Min. | Max. | Avg. |                        |
| 420 rpm              | 0.8  | 8.5  | 2.5  | 30                      |
| 600 rpm              | 1.2  | 12.1 | 3.5  | 22.5                    |
| 720 rpm              | 1.4  | 14.5 | 4.4  | 17                      |
| 1020 rpm             | 2.1  | 20.6 | 6    | 19                      |

The analysis of obtained results showed an increase in the average flow speed compared to the data from previous research [1]; the difference ranges from 1.5 to 4 m/s depending on speed of the mixing device. The maximum flow speeds in the simulation are equal for both mixing devices under different modes of operation. The minimum residence time of the fluids in the case of the existing mixing device is 2-fold more in comparison with three-blade device operating in diverse modes.

4. Conclusion

It was revealed that the time required for uniform distribution of flows ranged from 17 to 30 minutes. When increasing the rotational speed of the mixing device to 720 rpm and more, the time required for the uniform distribution of solutions in the reactor significantly reduced. Regarding mentioned above parameter, the efficiency of the three-blade mixing device was higher compared to the six-blade agitator under non-continuous operation mode. The average and minimum flows speed in reactors increased in comparison with the existing mixing device.

Considered type of the mixing device provides a more uniform distribution of phases in the reactor volume and significantly reduces the residence time of process media in the reactor.

**References**

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