Numerical Simulation of Polymer Dispersion Systems for Polymer Injection on Offshore Platforms

Zizhen Wang, Tianyang Li, Fangxiang Wang, Lin Guan, and Rui Zhang

ABSTRACT: Because of the limited space and high cost of offshore platforms, the dispersion and dissolution of the polymer are required to be of high efficiency, which is essential for polymer injection to enhance hydrocarbon recovery. The numerical simulation models of the water–powder mixing process by Venturi jetting and air-mixing were established. The multiphase flow fields in the water jet ejector, water–powder mixing head, and stirring tank were numerically simulated by FLUENT. Then, the distributions of velocity, volume fraction, pressure, and turbulent kinetic energy of each phase were obtained to evaluate the effects of polymer dispersion and the dissolution of the two mixing methods. According to the maximum velocity of the mixture at the Venturi jet, the optimized length of the throat is 25 mm in our models. The results of the air-mixing process show that a 120° angle of support rods has the best effect of water–powder mixing. The results of the present study show that compared with air-mixing, the combination of Venturi jet and the stirring tank can obtain a broader agitation range and more extensive effect on the flow field, which could uniformly disperse the polymer powder into water. This study has a guiding significance for the design of the onsite polymer injection process.

1. INTRODUCTION

With the continuous exploration and usage of oil and gas resources, conventional oil and gas reservoirs are gradually being exhausted, and stabilizing production is becoming more difficult, which severely affects economic benefits and energy security. Because most of the significant oil fields are mature fields, the use of enhanced oil recovery (EOR) is becoming more imperative. Many technologies are studied to facilitate mature field life extension: advanced reservoir characterization, artificial-lift optimization, conformance control, and various EOR schemes. Polymers have been frequently used to increase the areal and vertical sweep efficiency on oil recovery in the process of polymer flooding. With the use of conformance control agents, the addition of polymers in the injection water can increase its viscosity and thickening potential and thus changes the oil–water mobility ratio.

Because of the high cost of chemicals and low oil prices, it is essential to optimize polymer flooding strategies to shorten the polymer injection time and also maximize its economic efficiency, especially in the offshore oil fields. The mixing effect of polymer powder and water is a crucial issue in polymer flooding. There are two commonly used methods for the mixing process in the polymer injection system. The Venturi jet was invented by Eric Halliburton to rapidly mix a continuous supply of cementitious grout for cementing oil wells, which is an evolution of the idea of using a simple in-line static mixer obtaining excellent mixing performances. The Venturi mixing performance was improved by free-stream turbulence and mainstream swirl. Venturi jet is usually realized by a jet pump to form negative pressure to achieve mixing. The Venturi jetting is becoming the standard for a proportional to complete a mixture of two liquids in the process industry. Numerical and experimental studies on mixing behavior of Venturi jet, such as geometry optimization, device design, and mixing hydrodynamics, have received considerable attention in recent years. Air-mixing is another standard method to mix fluid, gas, or powder through the blower and pump, which has been widely used in the fuel–air-mixing apparatus, ventilation systems, and aerodynamic simulation. Many scholars have studied the mixing characteristics of jets under different exit shapes. For the polymer flooding in EOR, after the premixing by Venturi jetting or the air-mixing, the water–polymer powder mixture is transferred to the stirring tank for further mixing and curing. Considering the space limit and the high cost of offshore platforms, the polymer dispersion and dissolution equipment should be highly efficient, skid-mounted, and modularized. Although the ejector performance of the two premixing...
methods is well recognized, the systematic study on the polymer dispersion and dissolution is still insufficient. As an alternative approach, the nonlinear dynamic finite element method has become a useful complementary method for flow field simulation. This method has the advantages of (i) conveniently achieving single-factor control and (ii) minimizing uncertainties caused by human errors. Thus, a large amount of research studies have been carried out for numerical simulating the polymer dispersion and dissolution system. As present, simulation research studies are concentrated to determine the hydrodynamics of bubbly flow of a gas–liquid ejector within Venturi tubes and scrubbers. In this paper, first, the water–polymer powder premixing by Venturi water jet and the conventional air-mixing were simulated. Then, using the modeling results of these two premixing methods as the inputs, the subsequent water–polymer powder mixing within the stirring tanks was simulated and analyzed. This study can help to improve the development and application of polymer flooding of offshore oil fields.

2. RESULTS AND DISCUSSION

2.1. Numerical Simulation of the Venturi Water Jet Process. The Venturi water jet process is similar to the operating principle of the typical jet pump. The high-pressure pump outputs clean water with the predesigned pressure and volume, and then, negative pressure is formed in the Venturi jet ejector. The dry polymer powder is injected into the high-pressure pipeline through the funnel and then thoroughly mixed with the high-pressure fluid under the negative pressure. The mixture is injected into the stirring tank for further evenly distribution through the subsequent pipelines. In this view, the water jet injector is the most critical component. Here, we first simulate different parameters of the water jet injector. A typical Venturi jet model is shown in Figure 1. Usually, the polymer powder is added to the Venturi jet with an initial velocity according to the engineering practice on the offshore platform. In this modeling, assuming the polymer powder filling pipe is at the height of \( h = 400 \text{ mm} \) from the upper inlet of the Venturi jet. The polymer powder starts free-falling motion from the top of the filling pipe. Therefore, the inner diameter of the filling pipe \( (d_{\text{inner}}) \) is the critical factor to determine the mass fraction in simulation, which can be calculated by eq 1

\[
d_{\text{inner}} = \sqrt{\frac{4M_{\text{in}}}{\pi \rho v}}
\]  

where \( M_{\text{in}} \) is the filling mass flow of the polymer powder at the entrance, kg/h; \( v \) is the velocity of free falling of the polymer powder, m/h; and \( \rho \) is the bulk density of the polymer powder, kg/m³.

According to the actual field conditions, we design two sizes of Venturi jet \( (d_{\text{Venturi}}) \) and then simulate the two-phase flow of water and polymer powder. Here, the following shows the representative results of the modeling at two sizes of Venturi. When the polymer powder velocity at the entrance \( (M_{\text{in}}) \) is 200 kg/h, the inner diameter of the filling pipe \( (d_{\text{inner}}) \) is 4.59 mm, as calculated by the eq 1. Figures 2 and 3 show the flow field of the \( d_{\text{Venturi}} = 2 \text{ in.} \) Venturi jet. When the \( M_{\text{in}} \) is 50 kg/h, the \( d_{\text{inner}} \) is 2.29 mm. Figure 4 shows the flow field of the \( d_{\text{Venturi}} = 1.5 \text{ in.} \) Venturi jet.

![Figure 1. Process and structure of the Venturi water jet injector. The size of each unit can be changed with a different application.](image-url)
The maximum velocity of the water phase ($V_{\text{water}}$) and polymer phase ($V_{\text{polymer}}$), the generated negative pressure (TP), the maximum turbulence intensity (TKE$_{\text{max}}$), and the minimum turbulence intensity (TKE$_{\text{min}}$) can be directly obtained from Figures 2−4. The mass fraction of the dry polymer powder can be calculated by the mass flow rates of the water phase and the dry polymer powder phase. The results of the two sets of numerical simulations obtaining different polymer mass fractions are shown in Table 1. The velocity of the polymer phase is slightly higher than that of the water phase. The water flows mainly along with the Venturi in the water jet, and thus, the velocity of the water phase is equal to the horizontal velocity. While for the polymer phase, in addition to the horizontal velocity accelerated by the water flow, there is a vertical velocity after the free-fall motion from the tremie pipe into the funnel. The combined velocity of the polymer powder phase is higher than the velocity of the water phase. When the $M_p$ increases from 50 to 200 kg/h, the MF$_{\text{polymer}}$ obtained from numerical simulation also increases from 4921.5 to 10,128.9 ppm, which can meet the requirements on the different polymer mass fractions. In addition, when the mixture flows through the horizontal throat, the velocity increases, and the pressure decreases with the flow path shrinks. A negative jet pressure is formed, and the water in the lower portion of the funnel is sucked into the jet. The flow velocity of the central region of the jet is the highest, and the jet boundary expands continuously with the surrounding fluid inflow. The velocity of the central region gradually decreases because of the conversion of the kinetic energy between the jet fluid and sucked fluid.

Both the velocities of the water phase and the polymer phase increase rapidly after the horizontal throat (Figures 2 and 4). Meanwhile, the pressure rapidly decreases to form a two-phase jet, which achieves the negative pressure ejector of the Venturi jet. According to the distribution of the two-phase volume fraction, the length of the throat ($L_{\text{throat}}$) determines the mixing condition and the turbulence intensity. If the throat is too long, the energy is exhausted, and the outlet velocity becomes lower. On the other hand, the turbulence has not been stabilized if the throat is too short. Therefore, it is necessary to optimize $L_{\text{throat}}$. Here, based on the velocity and pressure cloud diagrams and the size of the Venturi jet, the $L_{\text{throat}}$ is selected to be 15, 20, 25, 35, and 45 mm in the $d_{\text{venturi}} = 2$ in. Venturi jet model. The relationship between the maximum velocity of the mixture at the outlet of the Venturi jet ($V_{\text{max}}$) and the $L_{\text{throat}}$ is shown in Figure 5. The influence of the $L_{\text{throat}}$ on the $V_{\text{max}}$ is first increased and then decreased, and an optimal $L_{\text{throat}}$ can be obtained. This is owing to that the mixing of the two parts (water and polymer) mainly occurs in the throat. The proper $L_{\text{throat}}$ can make the fluid mix well. If the $L_{\text{throat}}$ is too small, the jet would be separated. Therefore, we select 25 mm as the optimum $L_{\text{throat}}$.

### 2.2. Numerical Simulation of the Conventional Air-Mixing Process

The air-mixing process transports the polymer powder by gas and ejection water through a nozzle. After the gas, water, and polymer powder are mixed, then they are sent to a stirring tank for agitation. We simulate the gas−liquid−solid three-phase flow in the mixing head to obtain the required parameters, which are the main components of the air-mixing process. The physical model of the mixing head is shown in Figure 6. The physical model can reflect the internal structure of the flow field. In the entire flow field, 10 nozzles are uniformly distributed in a circle, and the support rods are uniformly distributed at an angle of 120° (Figure 7).
Two mutually perpendicular sections are selected to extract the calculation results. The results of the mixing head are shown in Figures 8−10. It can be further calculated that the mass flow rate of water is 13.75 kg/s, and the mass flow rate of dry polymer powder is 0.142 kg/s. Also, the mass fraction of dry polymer powder is 10,250 ppm, which meets the design requirement of the mass fraction (10,000 ppm).

The water phase causes a long potential core after flowing through the nozzles (Figure 8). The velocity after mixing with the other two-phases rapidly decreases, which is affected by the angle of the inner support rods. The velocities of the polymer phase and the gas phase sharply increase to form a high-speed zone at the location of the support rod bifurcation. A high-speed zone on both sides and a low-speed zone in the center are occurred after mixing with the water phase. Figure 9 shows that the water phase begins to fill in both sides of the upper position of the support rods. A boundary layer is formed when the gas phase and the polymer phase begin to mix after passing through the support rods. The volume of the pure water phase gradually decreases along the sidewall (Figure 9a). After the polymer phase encounters the support rods along the center flow channel, the distribution of volume fraction changes at the joint of the support rods (Figure 9b). The volume fraction along the inner side is relatively high. The polymer phase gradually diffuses with the increasing occupied volume after the support rods. The flow pattern of the lower region is the same as that of the polymer phase, while the gas phase is filled with the entire upper region (Figure 9c). Figure 10 shows the pressure distribution and the turbulent energy of the mixed phase. The pressure in the lower region tends to be stable, and the change in the turbulent energy is small after the three phases pass through the support rods.

It should be noted that the angle of the support rods has a high impact on the flow field; a suitable angle of support rods can make the fluid mix well. We simulate the air-mixing process with the different angles of support rods (from 90 to 150°) and calculate the relationship between the angles of support rods and the volume fraction of the polymer phase (Figure 11). As the angle of the support rods increases, the volume fraction of polymer first increases and then decreases, which means that an optimal angle of the support rods exists. The mixing of the three phases starts at the joint of the support rods. The small angle of the support rods may cause the intensity of turbulence too weak after the ejection, which further affects the uniformity of mixing. On the other hand, if the angle of the support rods is too large, the immense intensity of turbulence would cause a thin-mixed boundary layer, which also makes it difficult to achieve uniform mixing. Therefore, we choose 120° as the optimized angle of the support rods.

2.3. Numerical Simulation of the Flow Field in the Stirring Tank. According to the above-mentioned analysis, compared with the conventional air-mixing device, the water−powder mixing by Venturi jet can release from the sophisticated equipment, such as the blower, the dissolving tank, the nozzles, and support rods, which also significantly simplifies the liquid configuration, shortens the process flow, and reduces engineering investment.44

In the polymerization process, the Venturi jet and stirring tank are often used together. The water and polymer are initially mixed by the Venturi jet and then reach the stirring tank to continue mixing to achieve the best effect of water−
powder mixing. To study the flow field in the stirring tank, the initial conditions for the numerical simulation are set as the well-optimized velocities and volume fractions of the water and polymer powder obtained in the above water–powder mixing processes. The rotate speed of the stirrer is set as 120 rpm. The dispersion effect can be observed in the two mixing processes (air-mixing and Venturi jetting), respectively. According to the design, a physical model of the stirring tank and stirrer is established (as shown in Figure 12).

According to the simulation results of the 2 and 1.5 in. Venturi jet, the velocities and volume fraction of water and dry polymer powder are used as the initial conditions of the flow field in the stirring tank. The distribution of the velocity, pressure, water phase, polymer phase, and turbulence intensity map is calculated based on the following results. According to our modeling results, the polymer distribution in the stirring tank initiated by the above-mentioned two sizes of the Venturi jet is similar. Here, the flow modeling within the stirring tank initiated by the 1.5 in. Venturi jet is shown.

The relatively higher velocities of water (Figure 13a) and dry polymer powder (Figure 13b) near the stirrer indicate that the fluidity of the flow field at this point is better. In contrast, the mixed fluid of water and dry polymer powder at the location far from the stirrer has a lower velocity, especially at the corners of the stirring tank. The distribution of the velocity

Figure 9. Distribution of volume fraction in two mutually perpendicular sections. (a) Water phase, (b) polymer phase, and (c) gas phase. The directions of water and polymer powder injection are shown by the black arrows.

Figure 10. Distribution of pressure, turbulent energy, and velocity in two mutually perpendicular sections. (a) Three-phase pressure (Pa), (b) turbulent kinetic energy, and (c) mixed fluid velocity vector. The directions of water and polymer powder injection are shown by the black arrows.

Figure 11. Cross-plot of the angle of support rods and the volume fraction of the polymer phase.

Figure 12. Physical models of the stirring tank and stirrer.
vector in the whole flow field (Figure 13c) shows that the fluid in the stirring tank has a certain velocity, which is the evidence that the agitating action can affect the whole flow field. In addition, the water and the dry polymer powder are fully mixed after agitation; that is, the dry polymer powder can be better dispersed in the water. As can be seen from Figure 13f, the dry polymer powder can be evenly distributed throughout the flow field of the stirring tank with agitation. The volume fraction of the polymer powder at the top of the stirring tank is relatively high. At the same time, there is no significant increase in the volume fraction at the bottom, indicating that the polymer does not deposit at the bottom of the stirring tank. On the other hand, the turbulent energy is distributed throughout the flow field of the stirring tank (as shown in Figure 14). The turbulent energies near the stirrer are more intense because of the rotational motion.

The initial conditions are set as the simulation results of the water–powder mixing head. Figure 15a,b shows that the velocities of water and dry polymer powder are relatively high near the stirrer, which indicates that the fluidity of the flow field at these points is high. The thorough mixing of water and dry polymer powder means that the dry polymer powder can quickly disperse into the water. The velocity of the mixed fluid (Figure 15c) is low away from the flow field of the stirrer, especially at the corners of the stirrer. In addition, the distribution of the velocity vector in the whole flow field (Figure 15d) indicates that the mixed fluid in the stirring tank has an absolute velocity. Therefore, the agitating action can affect the entire flow field.

On the other hand, the dry polymer powder can be evenly distributed into the flow field of the entire stirring tank after agitation (Figure 16). In contrast, the volume fraction of the polymer phase at the bottom of the stirring tank has no significant increase, which indicates that the polymer does not deposit at the bottom and can be preferably dispersed throughout the water phase in the entire stirring tank because of the agitating action. Meanwhile, the turbulent kinetic energies distribute throughout the flow field of the stirring tank (Figure 16d), which is intense due to the rotational motion, especially near the stirrer.

2.4. Comparison of the Venturi Jet and the Air-Mixing. Based on the above analyses, the final mixing effect of the polymer within the stirring tank initiated by the 2 in. Venturi jet and the conventional air-mixing is compared. Figures 17–19 compare the distribution of the velocity, pressure, and turbulence intensity map between the two methods of ejecting polymers. Compared to the air-mixing method, ejecting the polymer into the stirring tank with the Venturi jet can obtain a broader agitation range and more extensive influence of the flow field in the stirring tank.
particular, it can be seen from Figure 19 that the Venturi tube is more capable of distributing the turbulent energy to the flow field of the entire stirring tank relative to the water–powder mixing head, which makes the turbulent energy more efficient because of the rotational motion in the vicinity of the stirrer. Also, Figures 17 and 18 indicate that with the combination of Venturi jet and the stirring tank, the polymer powder could be uniformly and thoroughly dispersed into the water, which is superior to the air-mixing.

3. CONCLUSIONS

The water–powder mixing method is a critical process in the injection stage of polymer flooding, especially for the offshore platforms with limited space and high cost. In this paper, numerical simulations were employed to investigate the dispersion and dissolution effects of ejecting polymers by...
Venturi jetting and conventional air-mixing. The main conclusions are summarized as follows:

(1) Based on the theory of fluid dynamics, the numerical simulation models of the water–powder mixing process by Venturi jetting and air-mixing were established. The multiphase flow field in the stirring tank was numerically simulated to obtain the distribution of velocity, volume fraction, pressure, and turbulent kinetic energy of each phase.

(2) Both the velocities of the water phase and the polymer phase increase rapidly after the horizontal throat of the Venturi jet. Based on the maximum velocity of the mixture at the Venturi jet, the optimized length of the throat is 25 mm. The results of the air-mixing process show that a 120° angle of support rods can make the fluid mix well.

(3) The mass fraction of the polymer dispersed and mixed by the two sizes of Venturi jet can meet the practical production. Compared with the conventional air-mixing method, the combination of Venturi jet and air-mixing method, the stirring tank can obtain a broader agitation range and more extensive influence of the flow field. The polymer powder could be uniformly and thoroughly dispersed into the water, which is superior to the air-mixing. The repeatability and accuracy of this study result could save much time and cost in the device design and provide references for the onsite polymer injection process for an offshore platform.

4. COMPUTATIONAL METHODS

A two-equation $k$–$\varepsilon$ turbulence model is used in Euler coordinates to quantitatively analyze the flow field with the assumption of a continuous medium in liquid and solid phases. The standard $k$–$\varepsilon$ model is known to be suitable for fully developed flow when the zone of interest is far from the boundaries. The flow field in the water jet injector is a complex high-speed flow, which is a typical turbulent flow state. The mass and momentum conservation equations are

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu \frac{\partial u_i}{\partial x_j} + \frac{\mu_t}{\sigma_t} \frac{\partial k}{\partial x_j} \right] + 2\mu_t \sigma_{ij} - \rho \varepsilon \tag{2}$$

where $\rho$ is the fluid density, kg/m$^3$; $u_i$, $v_j$, and $w$ are the components of the velocity in the $x$, $y$, and $z$ directions, respectively, m/s; $p$ is the fluctuating pressure, Pa; $\tau_{xx}$, $\tau_{yy}$, and $\tau_{zz}$ are the components of viscous stress in different directions, Pa; $P_x$, $F_y$, and $F_z$ are the components of quality stress, N.

This model is composed of one transport equation for the turbulent kinetic energy $k$ and one equation for the dissipation rate $\varepsilon$.

$$\frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\mu + \mu_t \frac{\partial k}{\partial x_j} \right] + 2\mu_t \sigma_{ij} - \rho \varepsilon \tag{4}$$

$$\frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\mu + \frac{\mu_t}{\sigma_t} \frac{\partial \varepsilon}{\partial x_j} \right] + \rho c_{\varepsilon} \frac{2s_{ij}}{s_{ij}} \varepsilon - \rho \varepsilon \frac{c^2}{k + \mu c/\rho} \tag{5}$$

$$\mu_t = \rho C_{\mu} k^2/\varepsilon \tag{6}$$

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

$$c_1 = \max \left( 0.43 \times \frac{\sqrt{2s_{ij} k}}{\sqrt{2s_{ij} k}} \right) \tag{8}$$

The exchange coefficient between the liquid and solid is calculated by the Syamlal–O’Brien drag model. The drag coefficient ($C_{D_p}$) is given by the Dalla Valle. The orbit of the discrete phase particles can be obtained by integrating the differential equation of the particle forces in the Lagrangian coordinate system. The force balance equation for particles in the Cartesian coordinate system (x-axis direction) is expressed as

$$\frac{d u_p}{d t} = F_D (u - u_p) + \frac{g_s (\rho_p - \rho)}{\rho_p} + F_X \tag{9}$$

$$F_D = \frac{18 \mu C_D k}{\rho_p d^2_p} \frac{Re}{24} \tag{10}$$

where $F_D$ is the unit mass drag of particles; $\rho$ is the density of the continuous phase; $u_p$ is the velocity of the particles; $u$ is the velocity of the continuous phase; $\rho_p$ is the density of the discrete phase; $Re$ is the relative Reynolds number; and $d_p$ is the diameter of the discrete phase.

The boundary conditions of the model are set according to the actual field conditions. The inlet speed in the filling pipe is set as 2.8 m/s. To ensure that the funnel is filled with water, the upper boundary of the funnel and the Venturi inlet is set as
the water speed. The outlet boundary with mixed fluid is the fully developed turbulent flow, and here we set as the free outflow boundary condition. The water phase on the wall meets the no-slip condition, which requires that the near-wall area in the calculation domain is treated by a wall function, and \( u, k \), and \( \epsilon \) at the wall are all zero. The particle phase satisfies the slip condition, which is typically referred to as a non-zero velocity at the solid surface because of a finite number of molecular interactions. The numerical simulation of the flow field in the air-mixing head is the same as the Venturi water jet process.

The flow field of the water jet injector is a complex 3D turbulent flow. For complex structures, meshing is a serious issue for numerical simulation. This study used an unstructured tetrahedral grid to ensure computational accuracy (Figure 20). Appropriate mesh encryption is applied for essential locations such as the Venturi’s part. The maximum value of the skewness is less than 0.85, and Global Competitiveness Index is less than 0.05. The total number of meshes is about \( 10^6 \) to \( 10^7 \) for each model. The computational time is closely related to the grid number, time step number, and hardware of the computer. The calculation time is about 10–24 h for a typical model.

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Notes
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