Numerical Simulation and Experiment on the Draining Sand Flow in the Jet Pump

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Abstract: Based on the reasonable assumption, applying standard $k-\varepsilon$ turbulent model and local refined meshes, the commercial software PHOENICS is employed to simulate the turbulent flow of the liquid-solid two phase in the jet pump. The distribution principle of axial velocity and concentration is obtained. The influence of the flow-rate ratio, the diameter and initial concentration of the solid particles on the concentrated distribution is particularly analyzed. Corresponding experiments are performed to confirm the results. The conclusions of the study can be used as reference for the design of draining sand using jet pumps.

1. Introduction
Draining sand with jet pumps is a solution to oil wells with sand production during the oil production process, which belongs to the hydraulic transportation of solid materials[1], typical of solid-liquid two-phase flow.

In early period, studies for solid-liquid two-phase flow[2] were mainly based on experiments, concentrating on dilute-phase flow of lower particle concentration because of the complexity of two-phase flow and the constraints of experimental means. With the development of the turbulence model theory and the rapid improvement of computer technology, numerical simulation has been widely used in the studies of two-phase flow[3] together with experiment study, which is another main means of two-phase flow studies.

Models to descript solid-liquid two-phase flow are: the dynamical model of single particle, the single-fluid model, the small slip model, the two-fluid model and Eulerian-Lagrangian model etc. These models are all approximation or simplification of the real process from different aspects, which can be applied in different scopes[4].

The turbulent flow of the liquid-solid in the jet pump is simulated by using the standard $k-\varepsilon$ turbulent model and commercial software PHOENICS[5] in the paper, based on the reasonable assumption. Corresponding experiments are performed to confirm the accuracy of the simulation results.

2. Basic mathematical model

2.1 Continuous phase control equation
Continuity equation
\[
\frac{\partial}{\partial t} (\rho u) + \frac{1}{r} \frac{\partial}{\partial r} (r \rho v) = 0
\]  
(1)

Momentum equation
\[
\frac{\partial}{\partial x} (\rho u^2) + \frac{1}{r} \frac{\partial}{\partial r} (r \rho uv) = 2 \frac{\partial}{\partial x} \left( \frac{\partial u}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial u}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v}{\partial x} \right) - \frac{\partial p}{\partial x}
\]  
(2)

\[
\frac{\partial}{\partial x} (\rho uv) + \frac{1}{r} \frac{\partial}{\partial r} (r \rho v^2) = \frac{\partial}{\partial x} \left( \frac{\partial v}{\partial x} \right) + \frac{2}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v}{\partial r} \right) + \frac{\partial}{\partial x} \left( \frac{\partial u}{\partial x} \right) - \frac{\partial p}{\partial r}
\]  
(3)

Turbulent kinetic energy \( k \) equation
\[
\frac{\partial}{\partial x} (\rho uk) + \frac{1}{r} \frac{\partial}{\partial r} (r \rho vk) = \frac{\partial}{\partial x} \left( \frac{\partial k}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial k}{\partial r} \right) + G - \rho \varepsilon
\]  
(4)

\[
G = \mu_t \left[ 2 \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial x} \right)^2 + \left( \frac{v}{r} \right)^2 \right] + \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial x} \right)^2
\]  
(5)

\[
k = \frac{1}{2} u'_i u'_j, \quad \varepsilon = \nu \left( \frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_i} \right)
\]  
(6)

Turbulent kinetic energy dissipation rate \( \varepsilon \) equation
\[
\frac{\partial}{\partial x} (\rho u \varepsilon) + \frac{1}{r} \frac{\partial}{\partial r} (r \rho v \varepsilon) = \frac{\partial}{\partial x} \left( \frac{\partial \varepsilon}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \varepsilon}{\partial r} \right) + \frac{\varepsilon}{k} \left( C_{1}G - C_{2} \rho \varepsilon \right)
\]  
(7)

In Eq (1-7), \( \mu_{\text{eff}}, \mu, \mu \) are effective viscosity, turbulent viscosity, dynamic viscosity respectively; \( k - \varepsilon \) model constants: \( \mu = 0.09, \quad C_{1} = 1.44, \quad C_{2} = 1.92, \quad \sigma_{k} = 1.0 \) and \( \sigma_{\varepsilon} = 1.3 \).

2.2 Discrete phase control equation

Continuity equation
\[
(\rho_{f} C_{s})_{,i} + (\rho_{f} C_{V})_{,i} = 0
\]  
(8)

Average momentum equation of the solid-phase
\[
(\rho_{f} C_{V,1} + \rho_{s} C_{V,1}), + (\rho_{f} C_{V} V_{1}), = -C_{1} P_{1} - C_{2} P_{1} + F \left[ C_{1} (U_{1} - V_{1}) - C_{2} (u_{1} - v_{1}) \right] +
\]
\[
[\mu_{s} C_{s} (V_{1,j} + V_{j,1}) + \mu_{s} C_{s} (V_{1,j} + V_{j,1})], - \frac{2}{3} \left( \mu_{s} C_{s} V_{1,j} + \mu_{s} C_{s} V_{j,1} \right), - (\rho_{f} C_{s} V_{1} + \rho_{f} C_{s} V_{j})
\]  
(9)

Concentration balance equation
\[
C_{i} + C_{j} = 1
\]  
(10)

In Eq (8-10), subscript \( f, s \) denote liquid-phase and solid-phase respectively; symbol “,” denotes partial derivative; \( U_{1} \) is time-average velocity components of liquid-phase; \( V_{1} \) is time-average velocity components of solid-phase; \( \rho \) is material density; \( \mu \) is dynamic viscosity; \( P \) is time-average pressure; \( C \) is volume concentration; \( g_{i} \) is gravity acceleration component in the direction \( i \); \( f_{i} \) is volume force components apart from gravity; \( F \) is interphase friction coefficient, for Stokes flow around the diameter of particles \( d_{p} \), \( F = 18 \mu_{f} / d_{p}^{2} \); \( K \) is local effects of momentum transfer from disperse phase to continuous phase.

3. Numerical simulation

3.1 Physical model
According to the actual size of jet pump, the calculated physical mode of the jet pump flow filed is set up by AutoCAD and then transferred to the PHOENICS-VR, the computational domain in cylindrical coordinates is shown in Fig.1.

![Fig.1 Schematic diagram of computational domain](image)

### 3.2 Meshing
Because of the non-regularity of the jet pump flow channel, flow channel changes in large-scale, local refined meshes are selected (in Fig.2), a total of 9200 \((1\times46\times200)\) nodes.

![Fig.2 Strid configuration](image)

### 3.3 Boundary conditions

#### 3.3.1 Inlet and outlet boundary conditions
According to the actual condition of oil wells, the axial velocity of the liquid-phase and the solid-phase are both estimated to be 10 m/s; sand diameter is 0.8mm and Sand concentration is 10\%. Using IPSA the two-phase calculated model, take the first-phase power fluid as water and its density is 1000 kg/m\(^3\); the second-phase is sand and its density is 1800 kg/m\(^3\).

#### 3.3.2 Wall boundary conditions
In the solid wall, the speed meets the no-slip boundary conditions; the wall-function method is applied near the wall; particles on the wall are complete elastic collision conditions.

### 4. The calculation results and analysis
Firstly, we define the non-dimensional flow ratio \(M\), the dimensionless pressure ratio \(P\) and the non-dimensional area ratio \(R\) respectively:

\[
M = \frac{q_3}{q_1} \\
R = \frac{A_j}{A_t} \\
P = \frac{p_2 - p_3}{(p_1 - p_2)}
\]

Where \(p_1\) is inlet pressure power fluid into the pump; \(p_2\) is outlet pressure of mixed liquor; \(p_3\) is inlet pressure inhalation liquid into the pump; \(q_1\) is volume flow of power fluid; \(q_3\) is volume flow of inhalation liquid; \(A_j\) is nozzle cross-sectional area; and \(A_t\) is throat cross-sectional area.

#### 4.1 Velocity distribution
Fig.3 is liquid-solid two phase axial velocity distribution. For liquid-solid two phase turbulent flow field, liquid and solid phase are different in terms of speed for the slip effect. The speed of liquid phase is faster than that of the solid phase after mixing. When entering the throat, both speeds are reduced, but the decrease of speed in solid phase is smaller than that of the liquid phase because of the function of solid phase inertial force, therefore, their speeds are the same in the exit of throat. After entering the diffusion tube, as the flow cross-section expands, the speed will be further reduced until the speed of
liquid decreased to below the solid-phase.

![Graph showing velocity distribution](image)

**Fig 3** Jet pump liquid-solid two-phase turbulent flow field velocity distribution

### 4.2 Concentration distribution

In the liquid-solid two-phase jet flow, the solid-phase concentration and its distribution have a considerable impact on turbulent jet flow field, as well as the basic function of the jet pump. Therefore, research on solid-phase concentration and its distribution can let us better understand the characteristics of the liquid-solid two-phase jet flow, making engineering applications more reasonable. To this end, the liquid-solid two-phase turbulent flow field in the jet pump is calculated, in condition that the solid concentration in the inhalation liquid is 10%, the solid-phase particle diameter is 1.0mm, and the flow ratio $M = 0.7972$. The concentration distribution is shown in Fig.4.

![Concentration distribution](image)

**Fig 4** Concentration distribution of jet pump liquid-solid two-phase turbulent flow field

As shown in Fig.4, power fluid (water) is exhausted at a high speed from nozzle, and the pressure drops rapidly. The liquid-solid mixture with a certain concentration of solid-phase is sucked into the mixing chamber by imbibition channel, mixing with power fluid. At the beginning of the mixing, as the radial velocity difference is large because of the high velocity power fluid, the mixing of inhale mixture and power fluid is carried out mainly depending on the convection; when entering the throat, the mixture further mixed with power fluid, solid-phase particles diffusing into the axis direction, so solid-phase concentration near the wall gradually reduced, while the solid-phase concentration near the axis gradually increased at the same time; when entering the diffusion tube, the liquid-solid two-phase mixed thoroughly, and finally two-phase liquid-solid is homogeneous, which exhibits that the concentration distribution curves overlap, as is shown in Fig.5 (digit in figure is the calculation grid number of radial throat).

Turbulent flow of jet pump is calculated separately for different solid-phase particle diameters, in the conditions that flow ratio $M = 0.797$ as well as the initial concentration $C_{0b} = 10\%$. The axial concentration distribution is show in Fig.6.

As shown in Fig.6, the solid-phase axial concentration distribution of jet pump is different because of the differences in solid-phase particle diameters. Firstly, the concentration distribution curve changes little at small particle diameter (<0.2mm); when the particle diameter is large (>0.2mm), the peak concentration appears in the throat exit for the reason that a plug is formed. Secondly, as
large-diameter solid-phase particles form a local concentration centralization, the time for liquid-solid two-phase concentrations achieving homogeneous becomes longer after entering the diffusion tube.

![Fig.5 The axial concentration distribution of solid-phase in different radial locations](image1)

**Fig.5** The axial concentration distribution of solid-phase in different radial locations

![Fig.6 The influence Solid-phase particle diameter on the axial concentration distribution](image2)

**Fig.6** The influence Solid-phase particle diameter on the axial concentration distribution

Assume the initial concentration of solid phase $C_{\text{0}} = 10\%$, the axial concentration distribution of the calculation turbulent flow field in different flow ratio is shown in Fig.7.

As is shown from Fig.7, with the increases of flow ratio, sand concentration increases after mixture with the share of solid-phase content increasing. At the same time, we can see that the high flow ratio, homogeneous mixed concentration curve shifting to the right, indicates a long required distance of fully mixing.

![Fig.7 The influence flow ratio on the axial concentration distribution](image3)

**Fig.7** The influence flow ratio on the axial concentration distribution

5. **Experimental study**

In order to verify the accuracy of simulation results, the basic parameters of jet pump are studied by experiment. Experimental setup is shown in Fig.8. Experiments are carried on in the condition that dimensionless area ratio $R = 0.250$, and the experimental medium are the water and sand. The results of the simulation are compared to the experimental data shown in Fig.9 and Fig.10.
1. circulating water channel; 2. power pumps; 3. flow regulator; 4. turbo flow meter; 5. jet pump; 6. mixing sand tank; 7. pressure transducer; 8. reversal valve; 9. digital display; 10. signal amplifier; 11. data acquisition system

6. Conclusions
(1) The contrast experiment result shows that it is feasible to adopt the standard $k-\varepsilon$ turbulent model and PHOENICS software to simulate the turbulent flow field of the solid-liquid two phase in the jet pump.

(2) When the diameter of solid-phase particle is smaller than 0.2mm, it is easy to form homogeneous flow, and the concentration distribution curve of solid-phase changes smoothly; when the diameter is larger than 0.2mm, as the infection of gravity difference and slip, solid-phase assembly occurs in the outlet of throat tube, and it is easy to form obstruction in actual applications.

(3) With the increasing of the flow ratio and the solid-phase concentration, the sand concentration increases at the same time, and the distance to mix fully is much longer than before.

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