Study on fluidization process in jet flow dredging device and the effects of device structure to sand collecting performance

Yue Zhang¹, Jinchun Song
School of Mechanical Engineering and Automation, Northeastern University, Shenyang, 110819, China
¹ Email: zhangyue12342280@sina.com

Abstract. The device structure has important influence on the sand collecting performance of jet flow dredging device. In order to study the effects of device structure, this paper presents a research for fluidization process of compact packing sand in jet flow dredging device. The calculation method which considers the cohesive strength between particles is proposed. The effects of arrangement of jet pipe and diameter ratio between jet pipe and suction pipe on sand collecting performance are studied. By comparison, we found that the structure of jet pipe inside suction pipe has better sand collecting performance than it outside suction pipe. With the jet velocity increasing, the pipe diameter ratio corresponding to the maximum concentration of particle phase at outlet reduces.

1. Introduction
Dredging equipment is widely used in many engineering fields, such as river dredging, reclaiming land from the sea, environmental protection dredging of rivers and reservoirs, port terminal building. Due to the jet flow dredging device has good environmental protection performance, the jet flow dredging device has been widely used in dredging engineering. It is important to study the fluidization process of sediment particles in pumping device to improve the performance of the system.

Many works have carried out relevant researches on sand-water two-phase flow. Kaushal et al. studied the relationship between sediment particles deposition, pressure and flow rate in the pipeline[1]. Liu yongbing et al. studied the effects of pipeline pressure drop and flow state of particles to particles deposition, by using two-fluid model[2]. Manoj and Kaushal researched the effects of interaction between sand and water on sand concentration distribution[3]. Chen zhijian used two-fluid model to study the resistance characteristics in dredging pipe[4]. Based on a mixture model, Liang lixin et al. successfully simulated fluid and suspended sediment motion in steady open-channel flows[5]. The above researches have effectively solved the problem of correlation analysis and calculation of sand particles in fluidized state.

During the fluidization process of sand particles in jet flow dredging device, particles have three flow states: compact packing state, dense flow state and dilute flow state. So the interaction between particles is different from particles in fluidized state.

Arrangement of jet pipe and diameter ratio between jet pipe and suction pipe are important parameters of jet flow dredging device design, which directly affect the efficiency of dredging.

In this paper, a two-fluid model of sand-water two-phase for fluidization process of compact packing sand in jet flow dredging device is proposed. This model is used to study the sand fluidization
process in different device structures. And the effect of jet pipe arrangement scheme and diameter ratio between jet pipe and suction pipe to efficiency of dredging are studied.

2. Jet flow dredging device and the model of fluidization process

2.1. Composition of jet flow dredging device

Figure 1 shows the schematic diagram of the jet flow dredging device. The part ② is jet pumps and ③ is jet pipe. The part ⑧ is suction pump and ⑤ is suction pipe. The jet pump press the high speed water spraying out from the jet pipe mouth, and sediment particles are fluidized by jet flow. The fluidized sand particles are sucked out by the suction pump through the suction pipe. The jet pump and the suction pump continuous work to collect sediment sand.

![Figure 1. Schematic of the jet flow dredging device.](image)

2.2. The model of fluidization process

When the device is operating, the sediment particles are fluidized and sucked out in compact packing state. In compact packing state, the gaps in particles are small, and the interactions between particles include friction, collision, and cohesive force formed by the attraction of particles. In the dense flow state, gaps in particles increases, the friction and cohesive force between particles decrease. In dilute flow state, gaps in particles are large, the interactions between particles are mainly collision, the friction and the cohesive force could be ignored without agglomeration of particles.

Based on the fluidization process of sand particles in the jet flow dredging device, the two-fluid model is used to describe the sand-water flow. The cohesion of particles is considered in compact packing state and dense flow state. But the cohesion is ignored in dilute flow state. According to the kinetic theory of granular flows[6-10], a two-fluid model of sand-water two-phase is established. The continuity equation and momentum conservation equation are as follow:

\[
\frac{\partial}{\partial t} (\alpha_L \rho_L) + \nabla \cdot (\alpha_L \rho_L \mathbf{v}_L) = 0, \quad (1)
\]

\[
\frac{\partial}{\partial t} (\alpha_s \rho_s) + \nabla \cdot (\alpha_s \rho_s \mathbf{v}_s) = 0, \quad (2)
\]
\[ \frac{\partial}{\partial t}(\alpha_i \rho_i \mathbf{v}_i) + \nabla \cdot (\alpha_i \rho_i \mathbf{v}_i \mathbf{v}_i) = -\alpha_i \nabla p_i + \nabla \tau_{ix} + \alpha_i \rho_i \mathbf{g} - \beta (\mathbf{v}_L - \mathbf{v}_s), \]  

\[ \frac{\partial}{\partial t}(\alpha_s \rho_s \mathbf{v}_s) + \nabla \cdot (\alpha_s \rho_s \mathbf{v}_s \mathbf{v}_s) = -\alpha_s \nabla p_s + \nabla (-\rho_s + \lambda_s \nabla \cdot \mathbf{v}_s + 2\mu_s \mathbf{S}_s + \tau_s) + \alpha_s \rho_s \mathbf{g} + \beta (\mathbf{v}_L - \mathbf{v}_s), \]

where \( \alpha \) is volume fraction; \( \rho \) is density; \( \mathbf{v} \) is speed; \( p \) is pressure; the subscripts \( L \) and \( S \) denote the liquid and particles, respectively.

\( \mathbf{S}_s \) is strain rate of the particle phase expressed as:

\[ \mathbf{S}_s = \frac{1}{2}(\nabla \mathbf{v}_s + \nabla \mathbf{v}_s^T) - \frac{1}{3} \nabla \cdot \mathbf{v}_s \mathbf{I}. \]  

\( p_s \) is the particle phase pressure[6,10]:

\[ p_s = \begin{cases} p_{sc} & \alpha_s < \alpha_{s,\text{min}} \\ p_{sc} + p_{fr} & \alpha_s \geq \alpha_{s,\text{min}} \end{cases}, \]  

\[ p_{sc} = \alpha_s \rho_s \Theta_s + 2\rho_s (1 + e_{ss}) \alpha_s^2 g_{0,ss} \Theta_s, \]  

\[ p_{fr} = F_{sr} (\alpha_s - \alpha_{s,\text{min}})^2 (\alpha_{s,\text{max}} - \alpha_s), \]

where \( p_{sc} \) is the particle pressure composed of motion and collision terms; \( p_{fr} \) is frictional pressure; \( \alpha_{s,\text{min}} \) is the critical frictional volume fraction of particles, \( \alpha_{s,\text{min}} = 0.5 \); \( \alpha_{s,\text{max}} \) is the maximum volume fraction of particles, \( \alpha_{s,\text{max}} = 0.63 \); \( e_{ss} \) is the collision recovery coefficient, \( 0 < e_{ss} < 1 \); \( g_{0,ss} \) is the radial distribution function; \( \Theta_s \) is particle temperature.

\( \lambda_s \) is bulk viscosity of particle phase[9]:

\[ \lambda_s = \frac{4}{3} \alpha_s \rho_s d_s g_{0,ss} (1 + e_{ss}) (\Theta_s / \pi)^{1/2}. \]  

\( \mu_s \) is shear viscosity of particle phase[6]:

\[ \mu_{s,\text{visc}} = \frac{4}{5} \alpha_s \rho_s d_s g_{0,ss} (1 + e_{ss}) (\Theta_s / \pi)^{1/2} \alpha_s \]

\[ + \frac{10d_s \sqrt{\Theta_s \pi}}{96\alpha_s (1 + e_{ss}) g_{0,ss}} [1 + \frac{4}{5} g_{0,ss} \alpha_s (1 + e_{ss})^2 \alpha_s]. \]

\( \beta \) is the drag coefficient[6,7]:

\[ \beta = \begin{cases} 150 \frac{\alpha_s (1 - \alpha_s)}{\alpha_s d_s^2} \mu_L + 1.75 \frac{\rho_L \alpha_s |\mathbf{v}_s - \mathbf{v}_L|}{d_s}, & \alpha_s \geq 0.2 \\ \frac{3}{4} C_D \frac{\alpha_s \rho_L d_s |\mathbf{v}_s - \mathbf{v}_L|}{\mu_L \alpha_s^{2.65}}, & \alpha_s < 0.2 \end{cases}, \]

\[ C_D = \frac{24}{\alpha_L \rho_L d_s |\mathbf{v}_L - \mathbf{v}_s|}, \]  

\[ \text{Re}_s = \frac{\alpha_L \rho_L d_s |\mathbf{v}_L - \mathbf{v}_s|}{\mu_L}. \]
In Eqs. (11) - (13), \( D \) is drag coefficient for single particle; \( \text{Re}_s \) is Reynolds number of particle phase.

\[
g_{0,ss} = \left[ 1 - \left( \frac{\alpha_s}{\alpha_{s,\text{max}}} \right)^{1/3} \right]^{-1}. 
\]

The transport equation of \( \Theta_s \) is given by [8,10]:

\[
\frac{3}{2} \frac{\partial}{\partial t} (\alpha_s \rho_s \Theta_s) + \nabla \cdot (\alpha_s \rho_s \mathbf{v}_s \Theta_s) = -\left( p_s I - \tau_s \right) : \nabla \mathbf{v}_s + \nabla \cdot \left( k_{\Theta_s} \nabla \Theta_s \right) - \gamma_{\Theta_s} + 3 \beta \Theta_s, 
\]

\[
k_{\Theta_s} = \frac{150 \rho_s d_s \sqrt{\Theta_s / \pi}}{384 (1 + e_{ss}) g_{0,ss}} \left[ 1 + \frac{6}{5} \alpha_s g_{0,ss} (1 + e_{ss}) \right]^2 + 2 \rho_s \alpha_s^2 d_s g_{0,ss} (1 + e_{ss}) \sqrt{\Theta_s / \pi}, 
\]

\[
\gamma_{\Theta_s} = \frac{12 \left( 1 - e_{ss}^2 \right) g_{0,ss}}{d_s \sqrt{\pi}} \rho_s \alpha_s^2 \Theta_s^{3/2}. 
\]

When the particles are packed in liquid phase, the particle phase needs to overcome the yield stress. Taking into account of friction and cohesive force between particles, the yield stress is written as:

\[
\tau_y = (\tau_c + \tau_f). 
\]

In Eqs. (18), \( \tau_f \) represents the frictional interaction between particles, and \( \tau_c \) represents the cohesive strength between particles.

\[
\tau_f = p_f \sin \phi \frac{S_x}{S_y}, 
\]

where \( \phi \) is the initial friction angle.

According to Cunben Tang, cohesive force is defined as [11]:

\[
\tau_c = \left\{ \begin{array}{ll}
\frac{n \alpha_{s,\text{max}}}{d_s} \left[ 2.5 \left( \frac{\alpha_s}{\alpha_{s,\text{max}}} \right)^{1.5} + 120 \left( \frac{\alpha_s}{\alpha_{s,\text{max}}} \right)^6 \right] & \alpha_s \geq \alpha_{s,\text{min}} \\
0 & \alpha_s < \alpha_{s,\text{min}} 
\end{array} \right. ,
\]

where \( |S_y| = \sqrt{S_x : S_y} \); \( n \) is coefficient of cohesive strength and its order of magnitude is \( 10^{-4} \) g/cm.

3. Simulation of fluidization process and effect of device structure

3.1. Simulation setup

In this paper, the CFD soft Fluent is used to simulate the fluidization process of sediment particles in the jet flow dredging device. The structural parameters and physical parameters are shown in Table 1.

The calculation area is shown in Figure 2. The upper boundary is the pressure inlet. The inlet of the jet pipe is the velocity inlet and the outlet of the suction pipe is the pressure outlet. Because of the structural symmetry, a 2D axial symmetry model is used to simplify the calculation. Simulations are performed for different cases, and the set of governing equation is solved using finite volume method. The phase-coupled SIMPLE algorithm is used for pressure–velocity coupling. A first order implicit discretization scheme is used for transient formulation and a first order upwind discretization scheme is used for the other terms. The calculation region is meshed in structured grid. The minimum grid size is \( 1 \times 1 \) mm. The simulation time step is 0.001s and the simulation time is 30s.
3.2. Simulation of fluidization process
When the device is operating, the sediment particles are fluidized in compact packing state. In order to study the technical performance of the jet flow dredging device, we have simulated the fluidization process of sediment particles.

Table 1. The structural parameters and physical parameters.

| Parameter                  | Value          |
|---------------------------|----------------|
| Diameter of jet pipe      | 6mm            |
| Diameter of suction pipe  | 30mm           |
| Height of sand bed        | 250mm          |
| Density of particles      | 2520 kg/m³     |
| Density of water          | 983 kg/m³      |

Figure 2. Schematic diagram of calculation.

Figure 3 and Figure 4 show the comparison curves of simulation and experiment for the fluidization process of sand particles. The jet flow velocity is 3.5 m/s. The averaged diameters of sand particles are 0.0565 mm and 0.112 mm, respectively. Figure 3 shows the relation between maximum radius of the fluidization area and collecting time. Figure 4 shows the relation between averaged mass concentration of particle phase and suction flow velocity at the outlet. In Figure 3, rz is maximum radius of the fluidization area, and r is radius of suction pipe. The simulation results agree well with the experimental results.

Figure 3. Relation between maximum radius of the fluidization area and collecting time.
3.3. Effects of device structure

In this paper, we have studied the effects of arrangement of jet pipe and diameter ratio between jet pipe and suction pipe on sand collecting performance in jet flow dredging device.

There are two typical arrangement schemes of jet pipe: the jet pipes are placed inside suction pipe and outside the suction pipe. Figure 5 shows the concentration distribution of particle phase in two structures at 10s. The particle size is 0.112mm, the velocity of jet flow is 3.5m/s, and the velocity of suction flow is 0.2m/s.

As can be seen from Figure 5, jet pipe arrangement scheme has important effects on sand collecting performance. When the jet pipes are placed outside, the fluidized area is large, and the fluidized sediment particles diffuse to outside of the suction pipe. The diffusion particles lead to secondary pollution to the surrounding water, and particles entering the suction pipe reduce due to the diffusion. When the jet pipe is placed inside, the fluidized area is small, and the fluidized sediment particles concentrate around the jet pipe, which causes little secondary pollution to the surrounding water. As there is little diffusion of particles, more sediment particles enter the suction pipe. The comparative analysis shows that the structure of jet pipe inside suction pipe has better environmental performance and higher sand collecting efficiency.

Figure 4. Relation between averaged mass concentration of particle phase and suction flow velocity at the outlet.

Figure 5. Concentration distribution of particle phase in two structures: (a) jet pipe inside, (b) jet pipe outside.
The diameter ratio between jet pipe and suction pipe has important effects on sand collecting efficiency in jet flow dredging device. A comparative study of different pipe diameter ratio is carried out in this paper. The pipe diameter ratios are 0.1, 0.15, 0.2, 0.3, 0.5 and 0.6, respectively.

Figure 6 shows the effects of pipe diameter ratios to the particle phase concentration at outlet with different velocities of jet flow. The particle size is 0.112mm, and the velocity of suction flow is 0.2 m/s.

It can be seen from Figure 6, when the jet velocity is 3 m/s, the maximum concentration of particle phase is at the region of pipe diameter ratio of 0.2 to 0.4. When jet velocity increases, maximum concentration of particle phase increases, and the pipe diameter ratio corresponding to the maximum concentration reduces. The pipe diameter ratio correspond to the maximum concentration increases with the jet velocity decreasing.

![Figure 6. Relation between pipe diameter ratios and particle phase concentration at outlet.](image-url)

4. Conclusion

(1) Taking into account of the influence of the cohesive strength between particles, we have established a two-fluid model for fluidization process of compact packing sand in jet flow dredging device in this paper.

(2) The structure of jet pipe inside suction pipe has better environmental performance and higher sand collecting efficiency.

(3) The sand collecting efficiency of jet flow dredging device is related to pipe diameter ratio, and the maximum concentration of particle phase at outlet is related to jet velocity. With the jet velocity increasing, the maximum concentration of particle phase increases, and the corresponding pipe diameter ratio reduces.

References

[1] D R Kaushal, Yuji T, R R Dighade. 2002 J Power Technology 125 89
[2] Liu Y B, Chen J Z, Yang Y R. 2006 J Journal of Zhejiang University: natural science 40 858 (in Chinese)
[3] Manoj K G, D R Kaushal. 2016 J Journal of Hydrology & Hydromechanics 64 261
[4] Chen Z J. 2017 D Wuhan: Wuhan University of Technology (in Chinese)
[5] Liang L, Yu X, Bombardelli F 2017 J Advances in Water Resources 107 108
[6] Ding J and Gidaspow D 1990 AICHE J. 36 523
[7] Savage S B, Jeffrey D J 1981 J Journal of Fluid Mechanics 110 255
[8] Jenkins J T, Savage S B 1983 J Journal of Fluid Mechanics 130 187
[9] Lun C K, Savage F B, Jeffrey D J, Chepurniy N 1984 J Journal of Fluid Mechanics 140 223
[10] Syamlal M, Rogers W, O'Brien T J 1993 MFIx Documentation: Volume 1 Theory Guide
[11] Tang C B 1981 J Sediment Research 2 60 (in Chinese)