High Pressure Jet Cans Technology Numerical Simulation and the Influential Factors of Cleaning Efficiency

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Abstract

During long time storage of oil, there will be oil contamination hanging in the oil tank wall and bottom, the oil contamination will not only occupy the capacity of the storage tanks, but also affect the inspection and maintenance of the storage tank. Therefore, it is necessary to clean the tank regularly. Mechanical tank cleaning has high efficiency, more secure, more environmental protection, and many other advantages relative to the artificial tank cleaning. So many enterprises now are gradually adopting mechanical method of tank cleaning for oil tanks. Changing the way of high pressure jet, such as changing the flow parameters, medium properties, nozzle motion parameters, concluding the optimal cleaning parameters by comparison, which can effectively improve the efficiency of cleaning. This paper based on the fluid dynamics theory to establish machine storage tank and nozzle calculation model, and through the user-defined function (UDF) to describe the movement of the nozzle. Combined with the VOF model and $k$-$\varepsilon$ turbulence model, simulating the flow field in the storage tank under different conditions. The results show that the optimal range of nozzle jet velocity is 28 m/s to 31 m/s; the optimal range of cleaning fluid temperature is 333 K to 338 K; the optimal range of rotating angular velocity of nozzle is 0.3 rpm to 0.5 rpm in the same oil cleaning process.

Key Words: High Pressure Jet, Tank Cleaning, Numerical Simulation, Dynamic Grid

1. Introduction

In the process of oil storage, due to the influence of gravity, temperature and pressure, the oil dirt, paraffin wax, sand, asphaltene and heavy metal salts will hang on the tank wall and settlement at the tank bottom. The greasy dirt will not only occupy the capacity of the storage tanks, but also affect the quality of the product and the maintenance of tank. According to statistics, the oil sludge in the storage tank reached up to 2.5 million tones one year in China [1]. Because of the sludge contains a lot of organic pollutants (phenol, benzene series, pyrene, anthracene, etc.), direct emissions will produce secondary pollution, so that increasing the difficulty of the oil tank cleaning.

Oil tank cleaning methods mainly include artificial cleaning, chemical cleaning and mechanical cleaning [2, 3]. At present, most enterprises are using manual method to clean tank in China, but this method is short of heavy human labor intensity, low safety, and long construction period, low oil recovery rate and so on. Obviously, artificial cleaning can’t achieve “green, economic and efficient” technical indicators [4–6]. Due to the chemical cleaning method need to use chemicals, easy to damage the environment and the investment is too big. Compared with the artificial cleaning tank and chemical...
cleaning tank, mechanical cleaning tank has the advantages of high efficiency, environmental protection, safety and so on [7]. Tank cleaning technology is developing by artificial cleaning to mechanical cleaning.

Mechanical cleaning tank technology is to apply cleaning fluid by machine injection under certain pressure, temperature and speed to the scale on the surface, remove the dirt on the surface and recycle the sludge. Cleaning medium is the same oil or crude oil. Mechanical cleaning tank process mainly includes: the oil transfer (transferred the crude oil in the clean oil tank to oil recovery tank for easy cleaning), the oil intermix (cleaner sprayed cleaning fluid breaking and dissolving the condensate oil and dirt on the oil tank wall and bottom, which would be dispersed and mixed. Lower the viscosity of the condensate oil and dirt), the same oil cleaning (dissolve the dirt on the oil tank wall and bottom by the heating pressure oil cleaning fluid), the warm water cleaning (add water to oil and water separation tank, after heating and pressure water, cleaning tank inside, the separation of the water continue to enter the warm water cleaning cycle operation until the oil tank clean end) etc.

Among them, the same oil directly influence on the cleaning efficiency of the tank cleaning process. To improve the efficiency of tank cleaning, RTR Rohoel Tank Reingung company in Germany developed a tank cleaning technology, the principle is using diesel as the cleaning fluid to clean the sludge adhered at the bottom of the floating roof tank, all the hydrocarbons can recycle, without manual work into the tank. Leigh oil services company in British designed the special cleaning robot water nozzle for nine large oil tank in Scotland, the principle of the technology is the sprinkler in tank movement up and down by water driven, crush the oil sludge with the hydraulic can save more than 50% of the operation time and manual labor. Rechtzigel A designed a high pressure nozzle with both ends injection [8]. Wang et al. used fluent to investigate the melting of waxy crude oil in the oil tank [9]. However, in order to improve the efficiency of mechanical cleaning tank, it is not enough to improve the nozzle. Still need comprehensive analysis of other influencing factors in the process of the tank cleaning [10]. In this paper, the factors affecting the efficiency of tank cleaning were analyzed. Using FLUENT software to make numerical simulation of flow field in the storage oil tank in the same oil cleaning process (the same oil cleaning flow chart shown in Figure 1), and with the help of UDF program control washing gun cycle rotation motion. Analysis the velocity and the temperature of the flow field inside the tank when mechanical spray gun with different rotation velocity and jet velocity and different temperature of cleaning fluid. Clear the effects of various factors on the tank cleaning efficiency. Gives the optimal range of parameters in the process of the mechanical cleaning tank.

2. The Theoretical Model

2.1 The Basic Control Model

Fluid follow the mass conservation, energy conservation and momentum conservation in the process of flowing [11]. Comprehensive unified three conservation equation to get mathematical expression:

\[
\frac{\partial}{\partial t}(\rho \varphi) + \text{div}(\rho \vec{u} \varphi) = \text{div}(\Gamma \text{grad} \varphi) + S
\]

(1)

where \(\rho\) is density of the cleaning fluid, \(\varphi\) is general variable, \(\Gamma\) is the diffusion coefficient, \(S\) is the source term.

2.2 The Turbulence Model

The fluid in the storage tank belongs to complex unsteady turbulent motion in the process of high pressure jet cleaning tank. Using the standard \(k-\epsilon\) turbulence model for numerical simulation of flow field inside the tank in the process of the same oil tank cleaning [12-15]. Consider the research object is fluid in oil tanks, so put the mixture assumed as incompressible fluid, to deal with the original equation, regardless of the custom of

![Figure 1. The same oil cleaning.](image)
the source term, \( G_b = 0, Y_M = 0, S_k = 0 \), as given by,

\[
\frac{\partial (p k)}{\partial t} + \frac{\partial (p k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] \\
+ \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \right) - \rho \varepsilon
\]  

(2)

\[
\frac{\partial (p c)}{\partial t} + \frac{\partial (p c u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_c} \right) \frac{\partial c}{\partial x_j} \right] \\
+ \frac{C_l \varepsilon}{k} \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{C_l \varepsilon}{k} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - C_{1c} \rho \varepsilon \frac{e^2}{k}
\]  

(3)

According to the value recommended buy Launder et which determined other empirical coefficient in the model, \( C_{1p} = 0.09, \sigma_k = 1.0, \sigma_c = 1.3, C_{1e} = 1.44, C_{2e} = 1.92 \).

Where \( k \) is common variables, \( \varepsilon \) is turbulent dissipation degrees.

2.3 The VOF Model

The original phase is the air in the storage tank, the crude oil after filling, in the same oil cleaning process. So determined the calculation model for the VOF model. In each control body, oil phase and gas phase volume fraction sum is 1 [16–21].

In the VOF model, according to solving the volume fraction continuous equation of one phase or multiphase to track the interface between the phase. On the first \( q \) phase is air, equation is shown below,

\[
\frac{\partial \alpha_q}{\partial t} + v_q \cdot \nabla \alpha_q = \frac{S_{\alpha_q}}{\rho_q} + \frac{1}{\rho_q} \sum_{p=1}^{n_p} (m_{q-p} - m_{q-p})
\]  

(4)

where \( m_{q-p} \) is the transport mass from the \( p \) phase (air) to \( q \) phase (oil), \( m_{q-p} \) is the transport mass from the \( q \) phase to \( p \) phase.

Attribute is determined by the split phase in each control volume, if the volume fraction of oil phase being followed in the same oil cleaning process. The calculation of density in each unit given by,

\[
\rho = \alpha_0 \rho_0 + (1 - \alpha_0) \rho_x
\]  

(5)

By solving the single momentum equation of all the area get the velocity field which shared by two phase. The momentum equation depends on the volume fraction of all phases through the properties of \( \rho \) and \( \mu \), as given by,

\[
\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \rho \left[ \nabla \cdot (\vec{v} \vec{v}) \right] + \rho \vec{g} + \vec{f}
\]  

(6)

Approximation of a shared area is limited, when the big differences of the velocity between each phase, calculation accuracy of the velocity close to the interface will be adversely affected.

The energy equation are shared by every phase, as given by,

\[
\frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\rho \vec{v} E) = \nabla \cdot (k_{\text{eff}} \nabla T) + S_h
\]  

(7)

where \( k_{\text{eff}} \) is effective thermal conductivity, \( S_h \) is the source term.

3. The Simulation Model

Used Solidworks software to set up the 3d model of storage tank and jet nozzle. Due to the large storage tank and the jet nozzle is much smaller, so opened round hole on the nozzle wall to simplify the structure of nozzle reasonably. The structure size of the storage tank and cleaning equipment as shown in Table 1.

Used ANSYS before processing software ICEM CFD to complete the mesh of oil tank model. Selected unstructured tetrahedral mesh, mesh of oil tank is shown in Figure 2, mesh of the nozzle is shown in Figure 3. Defined upper nozzle inlet boundary conditions for the velocity-inlet boundary, and nozzle and nozzle wall were

<table>
<thead>
<tr>
<th>Table 1. Geometry size of oil tank and nozzle simplified model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank type</td>
</tr>
<tr>
<td>-----------------------</td>
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<tr>
<td>Vertical storage tank</td>
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</tbody>
</table>
set to the interface boundary. In the setup interface, selected the coupled wall. The other boundary conditions of tank were the wall.

4. Results Analysis

4.1 Analysis of the Flow Field in the Storage Tanks in Different Inlet Velocity

Spray gun jet velocity directly affects the efficiency of mechanical cleaning tank, increase jet velocity can effectively break and remove the oil contamination attached at the tank wall and bottom, and the cleaning efficiency can be improved. But the too large velocity of gunshot will increase the unnecessary energy consumption, adversely affect the economic benefits; more important is the too large jet velocity will damage the walls of the storage tank. Changed the jet velocity in the process of the same oil cleaning tank to get the velocity flow field distribution of storage tank and numerical simulation to determine the reasonable range of jet inlet velocity, and the specific parameters in this model are shown in Table 2.

Figure 4 for xoz section velocity contours when jet velocity increased from 25 m/s to 34 m/s. Compared the

<table>
<thead>
<tr>
<th>Jet velocity/m s⁻¹</th>
<th>Density of cleaning fluid/kg m⁻³</th>
<th>Viscosity of cleaning fluid/mPa s</th>
<th>Temperature of cleaning fluid/K</th>
<th>Rotating angular velocity of nozzle/rpm</th>
</tr>
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<tbody>
<tr>
<td>25</td>
<td>880</td>
<td>40</td>
<td>333</td>
<td>0.1</td>
</tr>
<tr>
<td>28</td>
<td>880</td>
<td>40</td>
<td>333</td>
<td>0.1</td>
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Figure 4. xoz section velocity contours in different jet velocity.
velocity contours can be seen that different jet velocity obviously increased range of jet. However, nozzle was rotating in the process of cleaning, so analyzing xoy section velocity contours to comprehensively consider the jet velocity affect on the tank cleaning effect.

Figure 5 for xoy section velocity contours when jet velocity increased from 25 m/s to 34 m/s. From the velocity contours image contrast of horizontal section, it can be seen speed sweep area exist significant differences on the same section, and the greater the velocity the wider scope. For a better observation of jet velocity influence on the efficiency of tank cleaning, when the jet velocity was 25 m/s and 34 m/s, took five groups of axis level line parallel to the x axis from the bottom up 0.5 m, which interval for 1 m on xoy section and drew speed curve respectively, as shown in Figure 5.

The Figure 6 showed that velocity decreasing trend from the nozzle to the tank wall, this was due to gravity, gas resistance in the tank and the impact of factors such as fluid flow pattern. In the process of tank cleaning, although the jet velocity increased, the jet range and sweep region will increase obviously, the impact force will be enhanced. But jet velocity increase can also cause a large speed attenuation gradient. When the jet velocity of 25 m/s and 34 m/s, the velocity of the jet reached the tank wall were concentrated in the range of 15 m/s–20 m/s. Considered the above results analysis, determined the optimal range of the tank jet velocity is 28 m/s–31 m/s.

4.2 Analysis of the Flow Field in the Storage Tanks in Different Cleaning Fluid Temperature

Cleaning fluid temperature will directly affect the mechanical cleaning tank cleaning effect. Raise the temperature can be more effective to dissolve the oil contamination and improve the cleaning fluid and the oil mobility, thus improved the efficiency of tank cleaning. But cleaning fluid temperature can not be too high, due to mechanical cleaning tank is a long-term work, raise the temperature will cause the expenditure of energy, influence the economic benefits. High temperature can make the part of hydrocarbon component of oil and cleaning fluid volatile, increase risk of operation, and the specific parameters in this model are shown in Table 3.

Figure 7 for the xoz section temperature field under different cleaning fluid temperature. The higher cleaning fluid temperature caused the higher storage tank temperature, and oil contamination was easier to be cleaned. Considered the security and energy saving to make a detailed analysis to the storage tank temperature field, so took xoy section temperature contours from 0.5 m at the

Figure 5. xoy section velocity contours in different jet velocity.

Figure 6. Speed change curve of xoy section.
tank bottom under the condition of different cleaning fluid temperature. As shown in Figure 8.

Figure 8 can be seen that the high temperature area gathered from the bottom of 0.5 m on the horizontal section. The higher the temperature was, the storage tank temperature gradient was smaller, the high temperature area was greater. In order to get better observation of the influence of the cleaning fluid temperature on the tank cleaning efficiency. Took more groups of xoy section temperature values from the tank bottom different distances in different cleaning fluid temperature. Respectively drew temperature change curve, as shown in the Figure 8.

Figure 9 can be seen that temperature change trends reached the highest position in the center of the jet in the same line at different temperatures. Under the temperature of 323 k to 328 k had a good heating effect, and produced high temperature in the tank bottom and tank wall boundary. On the nozzle in the horizontal section, different jet temperature field produced by the temperature change was bigger, especially in the annular space produced high temperature area of the tank wall. High temperature area of 323 k and 328 k two models were obviously smaller and the average temperature was low. Considered when temperature was too high, the chemical reaction would happen between components of crude oil and the small amount of light crude oil group branch would come out. So made sure the cleaning fluid temperature optimum range was 333 k to 338 k.

4.3 Analysis of the Flow Field in the Storage Tanks in Different Jet Nozzle Rotating Velocity

Mechanical cleaning tank, nozzle keep periodically rotary motion, thus ensuring for 360° rotating cleaning tank. Too large spin angular velocity will cause to the impact force is too small, the tangential velocity is too large.
And too large spin angular velocity will cause cleaning velocity is too small, reduce the work efficiency. In order to ensure better cleaning efficiency, need to make sure that the optimal range of the rotating angular velocity of the nozzle, and the specific parameters in this model are shown in Table 4.

Figure 10 can be seen that, when the velocity was 0.1 rpm, the speed affected area was larger on the xoz section, but the jet velocity reached the wall was too small; when the velocity was 0.3 rpm and 0.5 rpm, speed affected area was reduced but the jet velocity reached the wall increased much, the jet impact velocity reached the wall and bottom was higher; when the velocity was 0.7 rpm, speed affected area and the jet velocity reached the tank wall had no obvious change compared with 0.5 rpm. Considered the rotating angular velocity of nozzle affected the radial velocity and axial velocity of the jet reached the tank wall and affected the cleaning effect So took the axial and radial velocity curve of multiple xoy section when the velocity was 0.3 rpm.

Figure 11 can be seen that axial velocity fluctuate in the center of the tank bottom, tank wall and jet area, mainly because the reverse from the tank bottom and

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tank wall to the fluid. The axial velocity of the other region was close to zero. The maximum radial velocity in the center of the jet, the closer distance of tank bottom, the smaller the radial velocity was, the larger axial velocity was. Took the velocity contours at the xoy level section at the distance of 0.5 m from the tank bottom in four different rotating angular velocity of nozzle. As shown in the Figure 11.

Figure 12 can be seen that, when the velocity was 0.1 rpm, due to the rotating angular velocity of nozzle was slower, less speed along the tank wall to spread, jet was not easy to break the oil contamination on the tank wall; when the velocity were 0.3 rpm and 0.5 rpm, speed affected areas obvious increased with nozzle rotating deflection, speed more obviously spread on both sides along

Figure 10. xoz section velocity contours in different rotating angular velocity of nozzle.

Figure 12. xoy section velocity contours in different rotating angular velocity of nozzle.
the tank wall, more conducive to clean oil contamination on both sides of the jet center on the wall; when the velocity was 0.7 rpm, due to the rotating angular velocity of nozzle was faster, compared to 0.5 rpm, swept area increased, but the velocity of the jet reached the tank wall decreased. Considered the above factors analysis to determine the optimal range of rotating angular velocity of nozzle was 0.3 rpm to 0.5 rpm.

5. Conclusions

(1) When cleaning fluid property parameters and temperature and rotating angular velocity of nozzle were same, analyzed the velocity field changes of each section in the tank at different jet velocity. Found that appropriately increased jet injection velocity could effectively increase the impact from the cleaning fluid. It was advantageous to break the oil contamination on the tank wall, reduce the time, cost of tank cleaning, increase the impact on affected area, and improve the efficiency of tank cleaning. Considered tank wall safety and energy efficiency factors, ultimately determined the optimization scope of the mechanical cleaning tank jet nozzle inlet velocity for 28 m/s–31 m/s.

(2) When cleaning fluid property parameters and jet nozzle inlet velocity and rotating angular velocity of nozzle were same, analyzed the temperature field changes of each section in the tank at different cleaning fluid temperature. Large variations in temperature field at different jet temperature especially produced high temperature area in the annular space of tank wall. Considered when the temperature was too high, there will be the chemical reaction between the crude oil composition, and the light group branch in the mixed crude oil will evaporate, thus optimized the cleaning fluid temperature range for 333 k–338 k.

(3) When cleaning fluid property parameters and temperature and jet nozzle inlet velocity were same, analyzed the temperature field changes of each section in the tank at different rotating angular velocity of nozzle. Found the change of rotating angular velocity can affect not only the swept area of cleaning fluid reach tank wall, but also can affect the velocity of the cleaning fluid arrived at tank wall. When the velocity was 0.3 rpm and 0.5 rpm, speed affected areas obvious increased with nozzle rotating deflection, speed more obviously spread on both sides along the tank wall, more conducive to clean oil contamination on both sides of the jet center on the wall. Therefore, optimized the range of rotating angular velocity of nozzle for 0.3 rpm–0.5 rpm.

References


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