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Numerical simulation and optimization of the dual circulation flow cleaning device for underground crude oil storage caverns

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Abstract. The underground oil storage cavern has the advantages of safety, large storage capacity and economical. It is widely used in the national strategic petroleum reserve and various commercial storage. In order to solve the problem of crude oil sludge deposition, this paper based on the principle of jet and the dual circulation flow cleaning method, using numerical simulation to verify the possibility of cleaning the cavern by the dual circulation flow, and the layout of the nozzle in the cavern is optimized and analyzed. The results show that in the 400m caverns, 25m spacing with a nozzle is the best layout spacing, but the circulation shape with different nozzle spacing is roughly same, even the 40m spacing between the nozzle can form a good dual circulation. The difference of nozzle spacing is mainly reflected in the average velocity of circulation. The overall velocity of the circulation increases with the increase of the nozzle spacing, but the rate of increase decreases with the increase of nozzle spacing.

Introduction

With the increase of petroleum demand and the pressure of national petroleum reserve, the underground crude oil caverns have advantages of less land, safety, high efficiency and large storage capacity. In the national strategic petroleum reserve planning, the underground cavern has been paid more and more attention[1-2]. When the crude oil is stored for a long time, the high viscosity oil sludge will be formed at the bottom of the cavern, causing problems such as the loss of crude oil, reduction of reserve and internal corrosion[3-4]. The main components of sludge deposits are crude oil and wax, which have certain recycling value. Unlike traditional oil depots, there has not yet been developed a complete system for oil sludge removal and cavern cleaning. Therefore, it is of great importance to solve the problem of sludge deposition and cleaning in underground caverns to improve the safe storage efficiency.

There are not much experience in the construction of underground caverns in China and many theories and techniques are not mature. The cleaning technology of petroleum tanks mostly adopt single circulation jet device for cleaning and stirring[5-7]. In long and narrow caverns, the pressure required by single circulation jet is high and the scouring effect is not good. On the basis of the existing method, this paper uses the dual circulation flow cleaning method. Using numerical simulation to verify the possibility of the dual circulation flow cleaning, make the optimum analysis on the layout of nozzles in the cavern, obtain a reasonable nozzle layout scheme and provide the experience for the design of the cleaning device in the future.

Computational methods

Governing Equations. The governing equations for turbulent flow in the present study are the continuity equations for mass conservation and unsteady Reynolds-averaged Navier-Stokes equations for momentum transport, as follows:

$$\frac{\partial u_i}{\partial x_i} = 0, i = 1,2,3 \tag{1}$$

$$r\frac{\partial u_i}{\partial t} + r u_j \frac{\partial u_i}{\partial x_i} = r F_i - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(m\frac{\partial u_i}{\partial x_j} - r\overline{u_i' u_j'}), i, j = 1,2,3 \tag{2}$$

Where i=1,2,3 represents X,Y,Z.direction respectively. $-r\overline{u_i u_j}$ is the Reynolds stress tensor, u is the averaged velocity, r is the density,in the present study.

There are several turbulence models employed to satisfy the governing equations in this similar study.The standard k - e model are chosen for use in this study. Transport equations of k and e in standard k - e model as:

$$\frac{\partial(rk)}{\partial t} + \frac{\partial(rku_i)}{\partial x} = \frac{\partial}{\partial x_i}\left[\left(m + \frac{m_t}{s_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - re - Y_m \tag{3}$$

$$\frac{\partial(rk)}{\partial t} + \frac{\partial(reu_i)}{\partial x} = \frac{\partial}{\partial x_j}\left[\left(m + \frac{m_t}{s_e}\right)\frac{\partial e}{\partial x_j}\right] + C_{1e}\frac{e}{k}(G_K + C_{3e}G_b) - C_{2e} r\frac{e^2}{k} + S_e \tag{4}$$

$$G_k = m_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{5}$$

Gk is the turbulent kinetic energy production caused by an average velocity gradient, Gb is the turbulent kinetic energy production caused by buoyancy, YM represents the effects of fluctuating expansion of turbulent on dilatation dissipation in compressible turbulent, C_{1e} , C_{2e} and C_{3e} are constant, s_k and s_e are turbulent Prandtl number of turbulent kinetic energy k and turbulent dissipation rate e , S_k and S_e are the user-specified source term.

The free surface is modeled by using Volume-of-Fluid (VOF) approach and a high-resolution interface capturing scheme, as (6).

$$\frac{\partial a}{\partial t} + \overset{\mathbf{v}}{v} \cdot \nabla a = 0 \tag{6}$$

Physical models and computational domain. In this paper, a numerical simulation method is used to optimize the layout array of nozzles in the cavern.In the middle of the cavern, there are many groups of bidirectional nozzles, two groups of circulation are produced in the cavern, which is suitable for the underground cavern with a long span.

In the numerical calculation, the size of the cavern is 400m long, 80m wide and 30m high. On the premise of jet flow, the liquid impact force per unit area of the thick oil sludge (bottom and both sides) and the average surface velocity are selected as the comparison parameters to optimize the layout of nozzles.

Based on the consideration of saving computing resources and time, the cavern model is established as a two dimensional plane with 400m long and 30m high. The numerical calculation of two-dimensional flow field is carried out. The calculation use the viscous flow model, liquid phase and gas phase analysis by using the VOF model, because of the jet nozzle is small, the nozzle model is simplified, the nozzle outlet is taken as the velocity inlet, and the computational domain is shown in Fig.1.

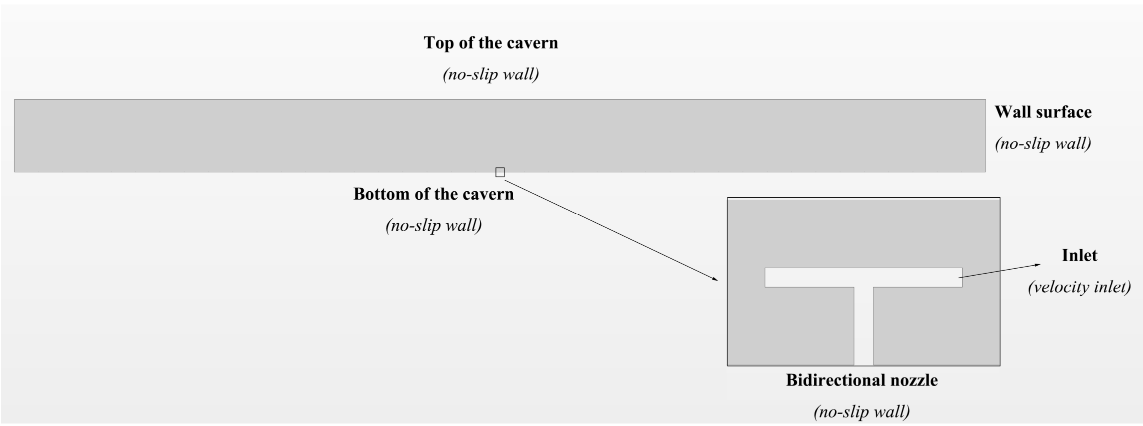

Figure 1. The computational domain of cavern model

Numerical results and discussion

Since there is no related device layout paper used as reference, 4 kinds of layout are calculated with reference to the layout of ground petroleum tanks and related patents[8]. In underground cavern's longitudinal midpoint began to set bidirectional nozzles, on both sides of every 10 m, 20 m, 25 m, 40 m with a unidirectional nozzle. During the cleaning, the central nozzle is a bidirectional jet, while the rest of the nozzle is a unidirectional jet, which can form two circulations in the cavern.The velocity of bidirectional nozzle is 40m/s, and that of unidirectional nozzle is 35m/s.The unsteady calculation method is chosen to calculate until the complete circulation is formed.

In the process of calculation, the velocity distribution cloud pictures are captured at regular spacings, and the velocity distribution pisctures in each stage of the circulation are captured and analyzed.

The circulation velocity of the 10m spacing nozzle. The circulation velocity of the 10m spacing nozzle is shown in Fig.2, as the number of the nozzle is the largest and the jet flow is the biggest. In theory, the wider spacing of the nozzle, the better effects of cleaning and mixing. But in the practical use, a large amount of liquid will be injected into the cavern in a short time, so that have an impact on subsequent cleaning. The general circulation is about 13 seconds. It can be seen that the circulation is fast, the jet velocity of the bottom is more than 25m/s, the velocity of the top and side wall is more than 15m/s and has good cleaning ability.

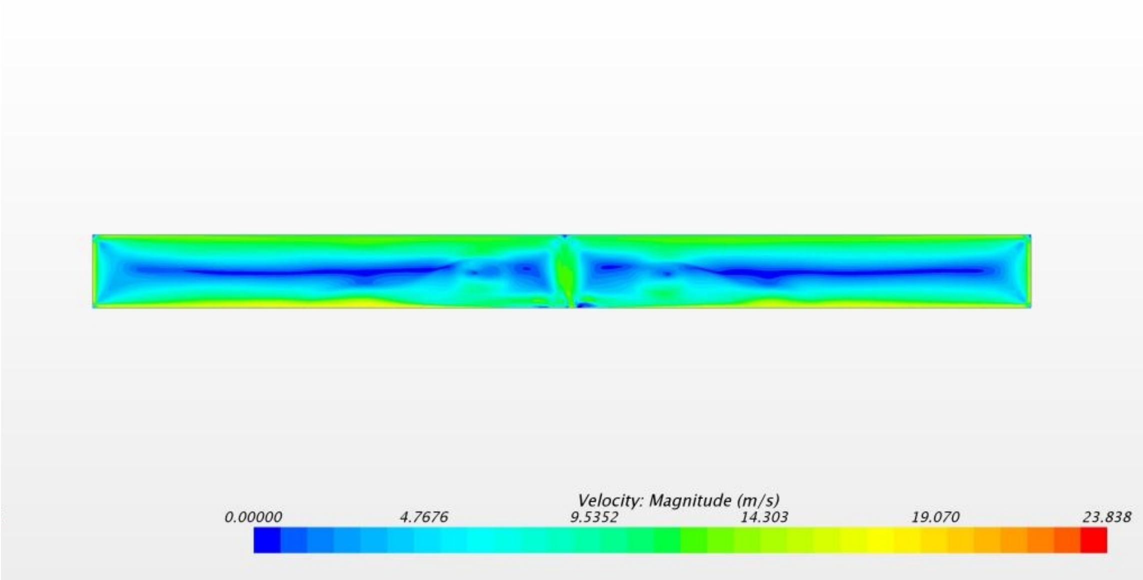

Figure 2. The circulation velocity of the 10m spacing nozzle

The circulation velocity of the 20m spacing nozzle. The velocity of the circulation in the 20m spacing cavern is shown in Fig.3. The formation time of the circulation is about 17 seconds, and the velocity around the cavern is relatively average, and the flow velocity is about 20m/s.

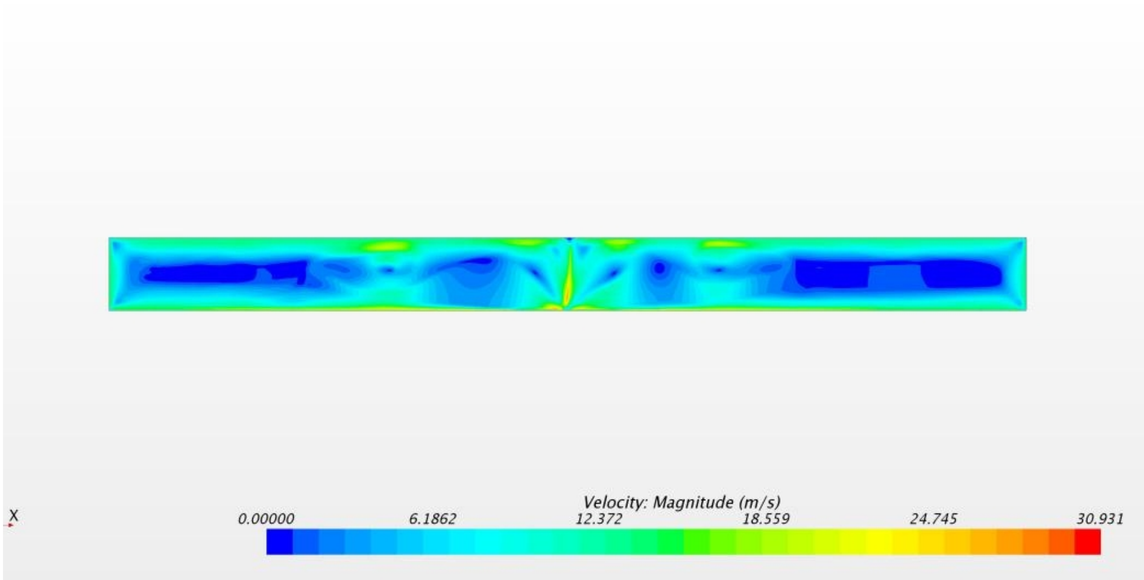

Figure 3. The circulation velocity of the 20m spacing nozzle

The circulation velocity of the 25m spacing nozzle. The velocity of the circulation in the 25m spacing cavern is shown in Fig.4. The formation time of the circulation is about 19 seconds, the velocity around the cavern is uniform and the bottom velocity is above 20m/s, which can effectively scour the bottom of the oil sludge, and the velocity of the wall surface and the top is around 15m/s, which can effectively remove the impurities and sludge.

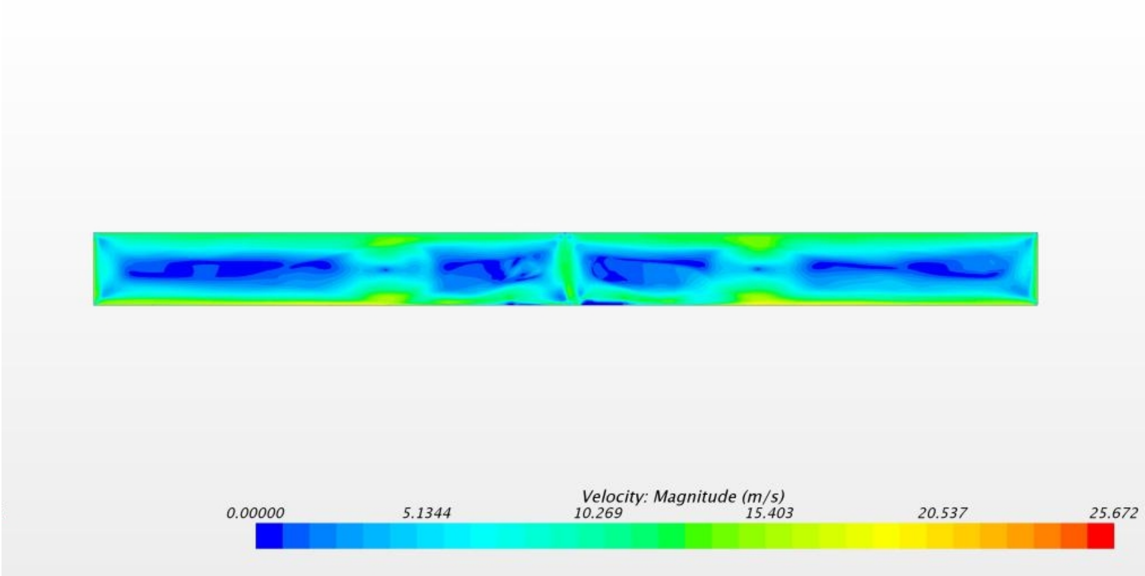

Figure 4. The circulation velocity of the 25m spacing nozzle

The circulation velocity of the 40m spacing nozzle. The velocity of the circulation in the 40m spacing cavern is shown in Fig.5. It can be seen that the bottom velocity has been reduced to 15m/s-20m/s, and the velocity of the wall surface and the top is below 15m/s. But there is a uniform low velocity area in the middle of the cavern, this is because the distance between two nozzles is too far, so the lateral velocity of the jet is seriously consumed.

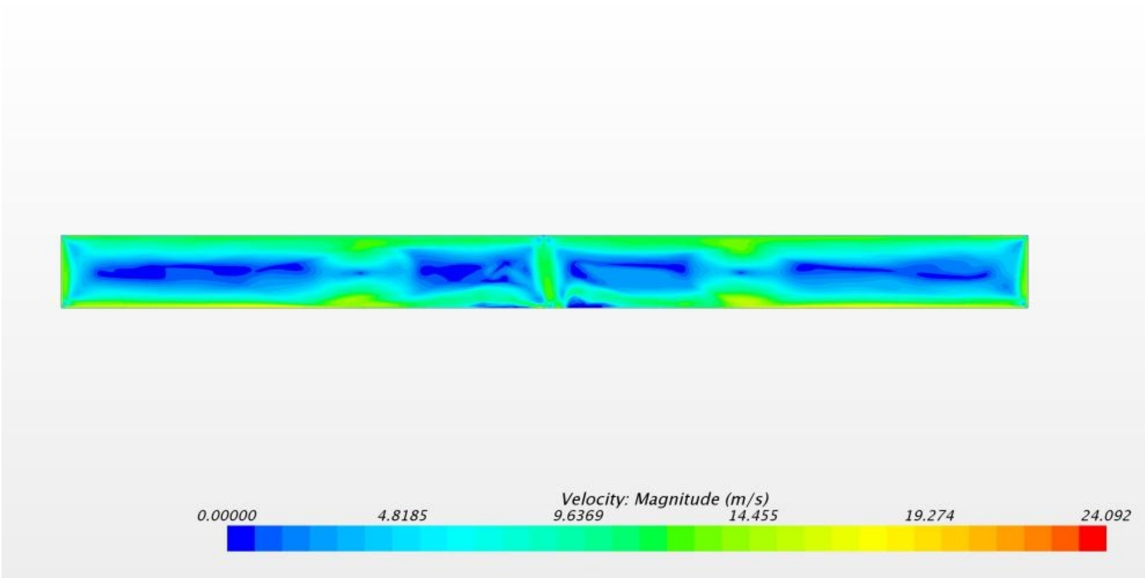

Figure 5. The circulation velocity of the 40m spacing nozzle

The data of circulation flow field under 4 operating conditions are extracted, and the pressure of the bottom surface is monitored. The turbulent kinetic energy, the average velocity and the outlet flow are compared in Table 1.

Table 1 Four types of flow field data

Spacing distance m	Pressure of the bottom Pa	Average turbulent kinetic energy J/kg	Average velocity m/s	Outlet flow $\times 10^3$kg/s
40	1284.9	15.42	4.73	0.74
25	2343.8	17.6	5.94	1.13
20	2782.7	17.7	5.97	1.26
10	6939.4	20.4	6.75	2.60

It can be seen from Table 4.1 that the pressure of the bottom increases with the narrowing of the spacing between the nozzle, which indicates that the clean-up ability of the bottom is enhanced with the decrease of the spacing. The average velocity and average turbulent kinetic energy are the average values of the whole calculation domain due to the calculation software factors. The average kinetic energy and velocity at the boundary around the cavern will be higher than the calculation results. The average turbulent kinetic energy and average velocity have been improved with the shortening of the spacing distance. However, with the shortening of the spacing, the number of nozzles also increased significantly, and the flow velocity increased subsequently. During the spacing from 20m to 10m, the overall velocity increased by 0.8m/s, the flow more than doubled.For the jet nozzle, the greater mass flow means the greater energy required. The energy consumption of the nozzle arranged at 10m spacing is much higher than that at 20m spacing, but the cleaning effect is similar.The 40m-spaced nozzle has a limited ability to clean up the sludge due to its slow bottom velocity.Therefore, the 25m is a good sapcing distance and has a good bottom cleaning velocity, which can also maintain a high velocity on the wall surface and the top to ensure the stability of the circulation.

Conclusions

In this paper, a numerical simulation is carried out for the dual circulation cleaning and stirring method, to understand the jet flow and circulation distribution in the cavern, and to optimize the nozzle's layout spacing. It is found in the process of comparative study:

1) The circulation shape of different nozzle intervals is roughly the same, and even the 40m interval between the nozzle can form a good dual circulation. The difference between nozzle intervals is mainly reflected in the average velocity of the circulation.

2) The overall velocity of circulation increases with the increase of nozzle spacing, but the increase rate decreases with the increase of nozzle spacing.

3) The velocity of the bottom surface of circulation is faster than that of the wall surface and the top, which is in line with the fact that the sludge accumulates more at the bottom.

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