Numerical simulation of suction and discharge valves’ motion in reciprocating waterflooding pump

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Abstract. The suction and discharge valves are the key hydraulic and wearing components in the reciprocating waterflooding pump, which have a significant influence on the operation stability and efficiency of pump. To investigate the valves’ dynamic working in the working processes, the numerical simulation of reciprocating waterflooding pump was carried out by Computational Fluid Dynamics (CFD) method. Based on the force characteristic on the valve plate, User Defined function and dynamic grid were adopted to define and update the valves’ dynamic parameters with the reciprocating motion of piston. The effects of spring stiffness coefficient and lift limit height on the transient motions of valves were investigated for the reciprocating waterflooding pump. The results show that the suction and discharge valves open or close in a short period. However, their motions lag behind the stroke when the piston reaches the left or right end point, especially for the discharge valve, which will lead to the larger impact effect and flow loss. Under various working parameters, the striking velocity on the lift limiter or seat is not always equal to the maximum velocity, and the valve plate is easily to vibrate in the suction process due to the pressure fluctuation and flow instability. The valve lifts, characteristic velocities and lag angles change in different ways with these three parameters, and the lag heights of discharge valve could exceed 3 times those of suction valve. The simulation results would provide a theoretical basis for the design of high-efficiency oilfield waterflooding pump.

1. Introduction
With the exploitation of crude oil, the oil production reduces greatly with the continually declining pressure and the resulting increasing oil viscosity in the oil extraction process [1]. In order to make up the underground loss, the waterflooding technology is commonly used to maintain the oil pressure and realize the high and stable oil production [2, 3]. As the key transport equipment, the waterflooding pump has a very important impact on the waterflooding system [4, 5]. At present, the China’s oilfield waterflooding system mainly uses two kinds of waterflooding pump: centrifugal pump and reciprocating pump, the latter of which has been developed rapidly in recent years because of its advantages with good pressurization performance, low maintenance cost, high water efficiency, economic benefits, and so on [6, 7].
The current researches on the hydraulic end of reciprocating pump are mainly focused on the suction performance of pump, the flow field analysis and the optimization of pump structure. Deng et al [8, 9] conducted the theoretical or experimental analysis on the motions of reciprocating pump or valve by establishing the momentum and mass conservation equations. Posch et al [10-12] simulated the velocity and pressure field of pump and valve numerically by using the Computational Fluid Dynamics (CFD) method. Muschelknautz et al [13, 14] obtained the influence factors of flow and pressure characteristics by the performance or flow field experiments. Yang et al [15] used Particle Image Velocimetry (PIV) to study the flow field distribution in the valve at different opening heights, and concluded that the main causes of valve failure were corrosion and wear.

Therefore, the suction and discharge valves are the key hydraulic and wearing components in the reciprocating waterflooding pump. Their structure and motions directly affect the operation and maintenance of reciprocating pump and waterflooding system. However, there are few literature on the motion law and impact characteristics of valves under the actual working of reciprocating pump. So it is necessary to understand the dynamic characteristic of valves in the reciprocating waterflooding pump deeply.

This paper aims to study the valves’ motion of reciprocating waterflooding pump by adopting the CFD method. The flow paths of pump cavity and valves are established, and the dynamic numerical simulation of hydraulic end is carried out to study the transient motions of suction and discharge valves with the crank angle under different parameters, so as to provide the basis for the design and development of high-efficiency waterflooding pump.

2. Object of study

Figure 1 shows the schematic of hydraulic end in the double-acting reciprocating waterflooding pump. The main structure and performance parameters of pump are: piston stroke $S = 200$ mm, piston diameter $D = 150$ mm, pump speed $n = 200$ r min$^{-1}$, suction pressure $P_s = 0.02$ MPa, discharge pressure $P_d = 10$ MPa. Both the suction and discharge valves are flat valves, and the total clearance volume $V_0$ is $2.1 \times 10^{-4}$ m$^3$.

For the suction and discharge valves, the valve plates are mainly subjected to the changing inertial force, spring force and static pressure on the upper and lower surfaces of valves in the opening and closing processes. In order to improve the overall stability and structural rationality of pump, the suction and discharge valves are limited to the maximum lift during their opening process. When the valve plate is opened to the maximum lift, there are two cases for the following motion of valves. One is that the valve plate strikes the lift limiter at a large velocity and rebound with a certain initial velocity. The other is that the striking velocity of valve plate is smaller, and the valve plate clings to the lift limiter until closing.

On the basis, the dynamic working of reciprocating waterflooding pump is investigated numerically for the whole stroke in CFD package.

3. Geometric Modeling and Numerical Solution

3.1. Geometric Modeling

In this paper, the flow region model of hydraulic end is established including the pump cavity and valves in the reciprocating waterflooding pump. The modeling and meshing of pump are conducted by using Solidworks and Gambit software. The meshes of flow region are shown in figure 2. Because of the irregular V-shape runners near the valves, the mesh errors are easily to appear when the fluid domain is updated dynamically. So the tetrahedral meshes are adopted for these regions, while the hexahedral structured meshes are adopted for the other regions.
3.2. Numerical Solution

3.2.1. Dynamic Grid Settings. During the working process of reciprocating waterflooding pump, the internal fluid flow is affected by the two kinds of moving boundaries: the reciprocating moving boundary of piston and the opening or closing moving boundaries of valves. In the simulation, the "In-cylinder" option of Fluent software is used to define the piston’s motion based on the crank link mechanism. And according to the force balance equations of valve plates, User Defined Functions are compiled to define the motions of suction and discharge valves separately in the actual working of waterflooding pump. The regions near the piston and valve plates are set as the dynamic grid zone, and the meshes are reconstructed with their motions at each time step.

3.2.2. Solution Settings. The Standard k-ε two-equation model is used as the turbulence model in the simulation. The PISO algorithm is used to solve the discrete equations. The Green-Gauss Node Based discrete method, which is more suitable for the tetrahedral element, is used for the gradient interpolation. The PRESTO method is used for the pressure interpolation. And the second order upwind and Quick formats are used for the interpolations of density, momentum and volume fraction, respectively.

The studied medium is a mixed liquid of water and additives. Its physical parameters are shown in table 1.

| Parameter       | Value   |
|-----------------|---------|
| Density (kg·m⁻³) | 996.5   |
| Viscosity (kg·m⁻¹·s⁻¹) | 0.00086 |

The initial conditions are set as the spring stiffness coefficients of suction and discharge valves $K_s = 3300$ N·m⁻¹, $K_d = 4000$ N·m⁻¹, the lift limit heights of suction and discharge valves $H_s = 6$ mm, $H_d = 8.5$ mm. The effects of spring stiffness and lift limit height on valves’ motions are studied further.

4. Results and discussions

4.1. Transient valve lift
The real-time valves’ positions are obtained with the crank’s movement, and the suction-discharge cycle of reciprocating waterflooding pump could be revealed.

Figure 3 shows the transient lifts of suction and discharge valves with the crank angle. It can be seen that the suction valve opens quickly as the crank rotates, and the suction plate stays attached to the lift limiter for a long time after reaching it. When the crank angle increases to around 164°, the suction plate begins to rise again with the slightly longer time than its opening time. So the suction valve is not completely closed at the end of piston’s suction stroke. As a direct result of this, the discharge valve opens much later and takes more time with the larger lift limit height, but the time that the valve plate is fully opened still accounts for 72% of entire discharge process. Although the discharge plate falls back more rapidly than the suction plate, the suction and discharge processes exceed the piston’s stroke in a cycle due to the gradually increasing lag performance of valves, which would affect the next working period of waterflooding pump. On the whole, the suction and discharge lift curves change smoothly during the movement of valves, and no vibration or rebound phenomenon occurs under the initial conditions.

![Figure 3](image)

**Figure 3.** Lift curves of suction and discharge valves under initial conditions.

Figure 4 and figure 5 show the changes of valve lifts under different parameters. The greater the spring stiffness coefficient, the longer the time required for the opening and closing of suction and discharge valves. With the increase of spring force, pressure difference on the valve plate is more difficult to overcome the resistance of spring, thus the end time of opening process become later and the start time of closing process become earlier. After a short compression, the opening of discharge valve is most significantly affected by the spring stiffness coefficient, while the opening time of suction valve and closing time of discharge valve just appear to have a slightly increasing linear trend.

![Figure 4](image)

**Figure 4.** Valve lift curves under different spring stiffness coefficients. 

\((H_s=6\text{ mm}, H_d=8.5\text{ mm}, n=200 \text{ r·min}^{-1})\)
As can be seen from figure 5, it is clear that the opening and closing time of suction and discharge valves both increase with the lift limit height. The changing trends of lift curves are almost coincident in the opening processes of valves, with the independent gradient of lift limit height. In contrast, the closing processes of valves are greatly influenced, and the valve plate appears the vibration phenomenon at the range of $\theta=150^\circ \sim 170^\circ$ when $H_s$ is greater than 20 mm. That may be because that the fluid flow is affected by the vortex flow and pressure fluctuation in the closing of suction valve, resulting in the instability of flow field in the pump.

4.2. Valve characteristic velocity

In the valves’ working process, the impact of valve plate on the lift limiter and seat aggravates its wear and impact fatigue. It is closely related to its motion, especially the maximum velocity and striking velocity, as shown in figure 6. The suction and discharge plates both open to the lift limiters at the maximum velocities under the initial conditions, which are equal to the striking velocities, and then the valve velocities decrease rapidly to 0. In the closing process, the obvious wave phenomena appear for the suction valve, and the striking velocities of valve are smaller than the maximum velocities. This may be caused by the instability of hydraulic force on the surface of valve plate. And it can be noticed that when the valve plate is near the lift limiter, the valve velocity fluctuates frequently in a short time, which does not have a significant influence on the lift of valve plate.

Figure 6. Velocity curves of suction and discharge valves under initial conditions.

Figure 7 and figure 8 show the changes of valve velocities under different parameters, and the corresponding characteristic velocities, such as $v_{om}(opening\ maximum\ velocity)$, $v_{os}(opening\ striking\ velocity)$, $v_{cm}(closing\ maximum\ velocity)$, $v_{cs}(closing\ striking\ velocity)$.
velocity), $v_{cm}$ (closing maximum velocity), $v_{os}$ (closing striking velocity), could be obtained, as shown in Figure 9 and figure 10.

![Figure 7. Valve velocity curves under different spring stiffness coefficients.](image)

![Figure 8. Valve velocity curves under different lift limit heights.](image)

With the increase of spring stiffness coefficient, the fluctuation of valve curves gradually weakens, and the opening and closing maximum velocities of suction and discharge valves both decrease in different degrees. Unlike the initial conditions, the opening striking velocities $v_{os}$ are slightly smaller than the opening maximum velocities $v_{om}$ under the bigger spring stiffness coefficient ($K_s \geq 6000$ N m$^{-1}$). And the differences between the closing striking velocities and maximum velocities reach the maximum (0.55 m·s$^{-1}$ and 0.28 m·s$^{-1}$) when the spring stiffness coefficient $K_s=4500$ N·m$^{-1}$ or $K_d=6000$·N m$^{-1}$. That is, increasing the spring stiffness of valve could weaken the impact and wear on the valve plate and seat, although the suction and discharge time of pump will be shortened.

The lift limit height has more obvious influence on the valve velocity and its changing trend. When $H_s \leq 15$ mm or $H_d \leq 8.5$ mm, the opening striking velocity is equal to the maximum velocity, which increases with the lift limit height. However, the opening striking velocity changes in the opposite way, and the opening maximum velocity remains constant for the larger lift limit height. It may be related to whether the driven force on the valve plate is enough and the velocity reaches its amplitude or not before the height of lift limiter. The closing maximum velocity and striking velocity both increase with the lift limit height. Especially for the closing maximum velocity of suction plate, it increases from 0.69 m·s$^{-1}$ to 3.01 m·s$^{-1}$ rapidly as the opening height increases from 6 mm to 25 mm.
4.3. Lag performance

It can be seen from the above studies that there are certain degrees of valve lag phenomena in the whole working process of waterflooding pump, which has a lot to do with the kinematic Westphal effect. The specific characterization parameters are that the angles lagging behind the piston stroke (opening lag angle and closing lag angle of suction valve, \( \theta_{o1}, \theta_{o2} \), and opening lag angle and closing lag angle of discharge valve, \( \theta_{d1}, \theta_{d2} \)) and the relative closing lag heights of suction and discharge valves \( \tilde{h}_{o}, \tilde{h}_{d} \), which are equal to the ratios of the lag heights to the lift limit heights.

Taking the initial case as an example, the relationship between the piston motion and lag performance of valves is illustrated in Figure 11. The motions of suction and discharge valves influence each other, and the lag property in the closing process of suction valve directly affects the opening and closing of discharge valve. For the actual working of waterflooding pump in the oilfield, the valve’s motion may also be affected by other various factors such as the unfiled cavity, liquid compressibility, gas content of liquid, clearance of mechanical transmission mechanism, etc., so the lag performance of suction and discharge valves may worsen. Then the transport capacity and efficiency of waterflooding pump would be reduced.

Figure 12 and 13 show the lag angles and heights of valves under different parameters. The changes of opening lag angles with the spring stiffness coefficient are just opposite to those of closing lag angles, which have the larger decreasing gradient (6.3° from \( K_s=3300 \text{ N·m}^{-1} \) to 5500 N·m\(^{-1} \)) for the suction valve and 6.8° from \( K_d=4000 \text{ N·m}^{-1} \) to 7000 N·m\(^{-1} \) for discharge valve). It can be seen that the effect of spring stiffness on the lag performance of suction valve is more pronounced than that of discharge valve. However, the opening lag angles of suction and discharge valves are hardly
influenced by the lift limit height, and the closing lag angles increase linearly with it except for $h_0=15$ mm. That is, an excessively large lift limit height of valve makes the lag characteristic and backflow rate aggrandize suddenly, which is not conducive to the stable and effective transportation of waterflooding pump. Furthermore, the relative lag heights of valves both decrease basically with the spring stiffness coefficient and lift limit height. Compared to the lag angles, the lag heights of discharge valve under different parameters reach more than 3 times those of suction valve. So even if the discharge pressure is higher, the backflow loss in the discharge process is more serious than that in the suction process, which is also a more noteworthy problem.

Therefore, considering the valve movement, service life, and flow loss, the valves with the spring stiffness coefficients of $K_s=4500$ N·m$^{-1}$, $K_d=5000$ N·m$^{-1}$ and the lift limit heights of $H_s=6$ mm, $H_d=8.5$ mm appear better overall performance for the reciprocating waterflooding pump.

![Figure 11. Relationship between piston motion and lag performance of valves.](image)

![Figure 12. Lag angles of valves under different parameters.](image)

![Figure 13. Lag heights of valves under different parameters.](image)
5. Conclusions
In this paper, the dynamic numerical simulation is conducted for the reciprocating waterflooding pump by using the CFD software Fluent. The transient lift, velocity and lag performance of suction and discharge valves are studied, and the effects of operation and structural parameters such as spring stiffness coefficient and lift limit height are analyzed further. The main conclusions are as follows:

(1) The suction and discharge valves both open and close rapidly in a short period. The time required for valves’ motions increase with the spring stiffness coefficient and lift limit height. The pressure fluctuation in the pump cavity may lead to the instability of valve plate, and the valve’s vibration phenomenon appears occasionally during the suction process.

(2) The characteristic velocities of valves all decrease with the spring stiffness coefficient, while the opening maximum velocity and striking velocity change differently with the lift limit height.

(3) The opening lag angles increase with the spring stiffness coefficient, and the closing lag angles are significantly affected by these two parameters in the opposite ways. The lag heights of discharge valve reach more than 3 times those of suction valve under different parameters.

(4) The spring stiffness coefficients of $K_s=4500$ N·m$^{-1}$, $K_d=5000$ N·m$^{-1}$ and lift limit heights of $H_s=6$ mm, $H_l=8.5$ mm are better parameters for ensuring efficient and stable operation of reciprocating waterflooding pump.

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