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Research Article

Failure Analysis of Erosion in Pump-Valve Rubber

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Abstract: The study is designed to explore the failure condition of valve rubber. A numerical simulation of solid-liquid two-phase flow was carried out by using the Euler model and FLUENT. We examined the influence of solid concentration, punching, taper angle and lift on pump-rubber erosion. An increase in solid concentration and punching rises the velocity of the flow field through valve play and the erosion wear is much dangerous. With an increase in taper and lift angle of the pump valve, the speed of the flow field decreases in the valve play and the erosion wear is weakened. The numerical simulation results agree well with the experimental observations, which verifies the reliability of the calculation method for pump-valve rubber failure and provides a reasonable basis for structure optimization.

Keywords: Erosion failure, numerical simulation, pump valve, rubber, solid-liquid two-phase flow

INTRODUCTION

Erosion wear is one of the leading causes of pump-valve rubber failure. Pump-valve rubber is eroded by fracturing fluid, the metal contacts in the valve disc are damaged and embedded rubber and rubber pieces form. The resultantly increased access to the gap-flushing valve and the risen body and seat contact with sand flow leads to early failure of the pump valve.

The abrasion mechanism of pump-valve rubber in the sand fracturing fluid is complicated and abrasion is caused mainly by abrasive and erosion wear. Most work in this field has focused on (Morris, 2014) the size (Zheng*et al*., 2015), concentration (Wang *et al*., 2002), shape (Grosch and Schallamach, 1966), load (Han *et al*., 2016) and rotating speed of wear (Uchiyama, 2007) on the rubber; rubber in the sand liquid of the abrasive-wear mechanism and the failure rules (Zhao, 2015). Arnold and Hutchings (1992) studied the erosion wear mechanism of elastic materials and found that erosion wear rate is related to the impact velocity, impact angle, particle size, elastic modulus and fatigue properties of the elements. Zuev and Chelmodeev (1968) discussed the effects of temperature and other factors on the erosion wear of rubber. Zhang and Wang (1993) and others had proposed four kinds of rubber material-abrasive erosion of physical models and physical processes. Peng*et al*. (2006) tested the erosion resistance of five types of rubber articles, discussed the relationship between the wear properties of several materials under the impact of rapid sand-laden flow and its features and found that polyurethane material exhibits a better anti-wear performance. Mo *et al*. (2015), Yang*et al*. (2008), Cai*et al*. (2011) andPeng*et al*. (2016) and others simplified the valve rubber material and valve body to integrate the internal flow field of the valve and obtained a distribution law of the gap flow field.

Most studies have simplified the valve body and rubber to one or have disregarded the impact of the valve rubber, but in the presence of high-pressure fracturing fluids, rubber wear is often faster than valve disc wear and valve-rubber failure leads to early valve failure. We studied the influence of solid concentration, punching, taper angle and lift on pump-rubber erosion by using Fluent software and obtained an understanding of the erosion mechanism. The work aimed to study the failure mechanism of erosion wear of valve rubber, provide a reference for optimizing the valve-structure design and improve the valve life.

MATERIALS AND METHODS

This study was conduct in Southwest Petroleum University from March 2016 to August 2017. L.M. and P.Y. conceived and designed the study; L.M., Z.C.Z. and G.C.Z. carried out the numerical simulation; P.Y. and L.T. analyzed experimental results. L.M. and P.Y. wrote the manuscript. L.M., P.Y., Z.C.Z., G.C.Z. and

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Fig. 1: Failure pump-valve rubber

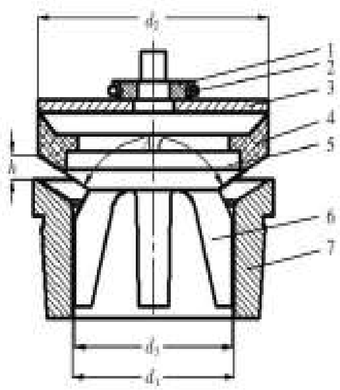


Fig. 2: Fracturing pump hydraulic end structure: 1. clasp, 2. circlip, 3. spring plate, 4. pump rubber, 5. valve plate, 6. guide pawl, 7. seat

L.T. reviewed and edited the manuscript. All authors read and approved the manuscript.

Analysis of failure modes of valve rubber: Pump-valve rubber works with fracturing fluid that contains solid particles. Abrasive and erosion wear are the main reasons for the failure of the pump rubber. Erosion of the sand-fracturing fluid causes holes in the lower part of the rubber. The valve rubber experiences a periodic impact of the valve seat and leads to fatigue failure and the valve seat impacts the lower edge of the rubber body.

Although the collapse of the upper part of the rubber reduces the performance, the cause of its failure is abrasive wear because the rubber length exceeds the length of the valve-seat sealing surface. When the valve functions incorrectly because the seat interacts with the rubber part with abnormal wear and tear, an increase in wear and tear results in accumulation in boundary deformation. Under an impact load, the collection of strain will produce a stress concentration and crack initiation. The cracks will continue to expand until the material breaks off. Samples of pump rubber that have experienced severe failures are shown in Fig. 1. The lower part of the pump rubber forms a honeycomb and the upper and lower edges exhibit massive peeling. In addition to the usual wear marks, the upper portion of the rubber is also deformed. Erosion wear is one of the main reasons for the failure of the rubber ball valve. To improve its working performance, we carried out a numerical simulation of the erosive wear of valve rubber.

Calculation model: The fracturing pump structure as shown in Fig. 2 consists of the plunger, suction valve, valve, crank and cylinder.d_1 is the diameter of the valve seat, d_2 is the diameter of the valve body, d_3 is the diameter of the guide paw and h is the lift of the valve plate. By exposing the fracturing pump hydraulic end to plunger reciprocating motion, mechanical energy can be converted into hydraulic power and yield suction and discharge valve opening and closing. To study the fracturing of fracturing valve rubber wear, we considered the valve flow-field model with valve rubber and we analyzed the distribution of flow-state parameters at the rubber. A calculation of the basin model was established via Pro/E and included the valve-rubber mechanical structure. The model of the valve-body structure was simplified by removing the guide paws and the stem and spring structure. The Boolean operation was used to provide a watershed model fluid. Because the model is symmetrical, half of

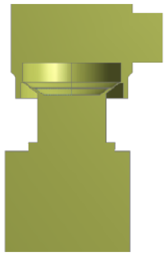


Fig. 3: The three-dimensional model of pump valve

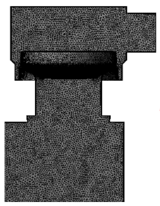


Fig. 4: Valve grid model

Table 1:Parameters of watershed model boundary conditions

Crank angle (φ/°)	Valve lift (*h/mm*)	Body speed (*m/s*)	Plunger speed (*m/s*)
24	1.17	0.141	1.147
34	2.02	0.724	1.596
44	4.84	0.507	2.014
54	6.23	0.350	2.388
64	7.47	0.245	2.708
84	8.81	0.083	3.132

the model was analyzed. Figure 3 shows a three-dimensional model of the pump valve.

Meshing and boundary conditions: Because the computational watershed model is much complex, the hexahedral mesh was divided automatically by the mesh module in the workbench to achieve a smooth division of the grid and the subsequent flow-field calculations. To improve the calculation accuracy and to save calculation time, the valve play should be appropriately encrypted. The global unit size was 4 mm and when divided into a grid with five expansion layers, the results generated 291569 nodes and 1049110 grid units (Fig. 4).

The boundary conditions were as follows:

Fracturing-pump working medium: the sand content of 20% to 40% of the fracturing fluid, the solid phase for the quartz sand

Fracturing-fluid density: 1200 kg/m^3

Fracturing-fluid viscosity coefficient: 0.05 kg/ms

Solid density: 2200 kg/m^3

Solid-phase average particle size: 0.4 mm

Inlet speed: same for liquid and solid phase

Pressure outlet: 78 MPa

Symmetry conditions: because the entire model is symmetrical, use a symmetry plane

Solid-wall conditions: no slip, near the wall using a standard wall function

Initial conditions: the volume fraction of sand at the inlet was 20% as the initial condition

The relevant parameters of the watershed model boundary conditions are shown in Table 1.

Numerical model: The fracturing pump hydraulic end of the working medium was sand fracturing fluid, so the liquid flow field can be seen to be a complicated flow of solid-liquid two-phase flow. The following assumptions were made (Qu*et al*., 1996):

- The fluid experiences Newtonian flow and flows continuously throughout the hydraulic end
- The liquid phase is an incompressible fluid and the solid phase consists of uniformly sized spherical particles
- The solid and liquid phases experience no phase change, regardless of the flow-field cavitation phenomenon.

The Euler multiphase model uses a particulate phase as a quasi-fluid and considers that fluid and particles co-exist and penetrate each other. If we ignore the effects of temperature changes, regardless of the energy equation, the control equations based on the Euler model are established as follows:

- Continuity equation:

$$\frac{\partial \alpha_l \rho_l}{\partial t} + \nabla(\alpha_l \vec{v}_l \rho_l) = m_{sl} \tag{1}$$

where,

α_l =The liquid volume fraction
$\vec{v}_l$ =The liquid velocity
ρ_l = The physical density of the liquid phase
m_{sl} = The mass-transfer coefficient between the solid phase and the liquid phase

- Liquid momentum-conservation equation:

$$\partial(\alpha_l \rho_l \vec{v}_l) + \nabla(\alpha_l \rho_l \vec{v}_l \vec{v}_l) = -\alpha_l \nabla P + \nabla \bar{\bar{\tau}}_l + \alpha_l \rho_l (\vec{F}_l + \vec{F}_{lf,l} + \vec{F}_{vm,l}) + \alpha_l \rho_l g + k_{sl}(\vec{v}_s - \vec{v}_l) + m_{sl} \vec{v}_{sl} \tag{2}$$

where,

P =The liquid pressure
$\vec{F}_l$ =The external force of the liquid phase
$\vec{F}_{vm,l}$ = The liquid-phase virtual mass force
$\vec{F}_{lf,l}$ = The liquid-phase lift force
$\bar{\bar{\tau}}_l$ = The shear stress tensor between the liquids
g = The gravitational acceleration
$\vec{v}_s$ = The solid-phase velocity

$\overrightarrow{v_{sl}}$ = The velocity of the phase
k_{sl} = The momentum-exchange coefficient between the solid phase and the liquid phase.

- Solid-state momentum-conservation equation:

$$\partial(\alpha_s\rho_s\vec{v_s})+\nabla(\alpha_s\rho_s\overrightarrow{v_s v_s})=-\alpha_s\nabla P-\nabla P_s+\nabla\bar{\bar{\tau}}_s+\alpha_s\rho_s(\vec{F_s}+\overrightarrow{F_{lf,s}}+\overrightarrow{F_{vm,s}}) +\alpha_s\rho_s g+k_{ls}(\vec{v_l}-\vec{v_s})+m_{ls}\overrightarrow{v_{ls}} \quad (3)$$

where,
P_s = The solid-phase pressure
$\vec{F_s}$ =The solid-phase external bulk force
$\vec{F}_{vm,s}$ = The solid-phase virtual mass force
$\overrightarrow{F_{lf,s}}$ = The solid-phase lift
α_s = The solid volume fraction
$\bar{\bar{\tau}}_s$ = The solid shear stress tensor
k_{ls} = The momentum-exchange coefficient between the liquid phase and the solid phase
m_{ls} = The mass-transfer coefficient between the liquid and solid phases

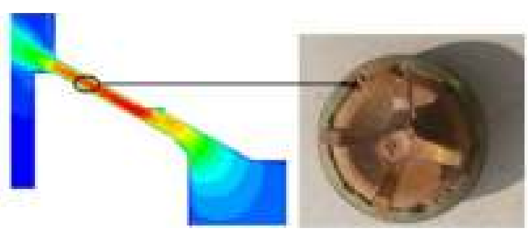
Erosion performance prediction: When the surface of the valve rubber with a significant amount of sand-fracturing fluid makes contact and experiences relative movement, surface loss of the valve rubber results from wear erosion. Because the fracturing fluid consists of solid-phase particles in a two-phase fluid, the valve rubber-erosion time is short and the flow is in a complex state, the flow rate of the dual solid-liquid phase is higher, the impact is more significant and the valve rubber is exposed to more erosion damage. Therefore, the speed of play of the drilling-pump valve reflects the extent of erosion wear.

RESULTS AND DISCUSSION

Failure analysis and reliability validation: To study the influence of solid concentration, particle diameter, punching, taper angle and lift on the pump-valve rubber, we calculated the velocity distribution of the dual solid-liquid phase at the gap. Based on the initial conditions, the flow field was simulated under five different working conditions.

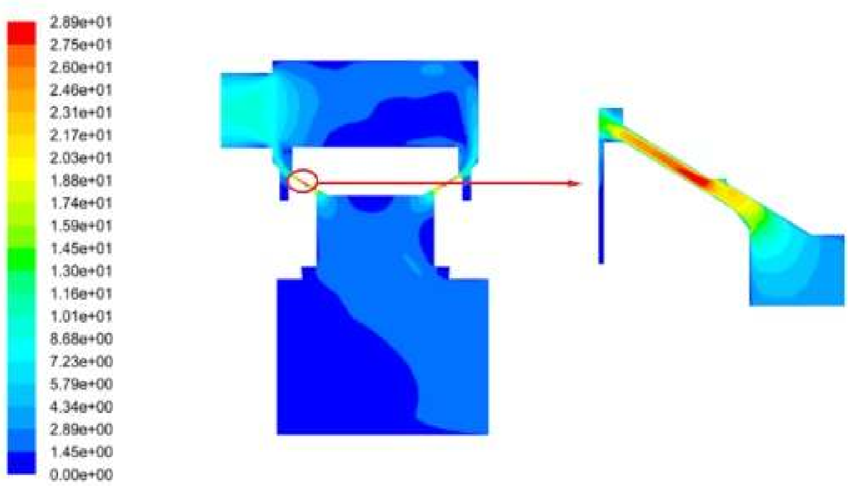
The diameter of particles in the fracturing fluid is large, the particle inertia is extensive and the fluidity is terrible. In the bottom of the structure and at greatest turbulent kinetic energy, solid particles exist in the fracturing fluid with chaotic movement and these cannot follow the liquid along the gap and continue to flow, which results in an accumulation of solid particles. The concentration of solid phase at this point is high and the top level of accumulated sand in this area can cause erosive damage to the lower ring region. The valve rubber under the ring increases, the particle concentration is also more substantial and most sand near the central location is washed.

The simulation model of the fracturing pump basin modelisshown in Fig. 5a and the field-failure

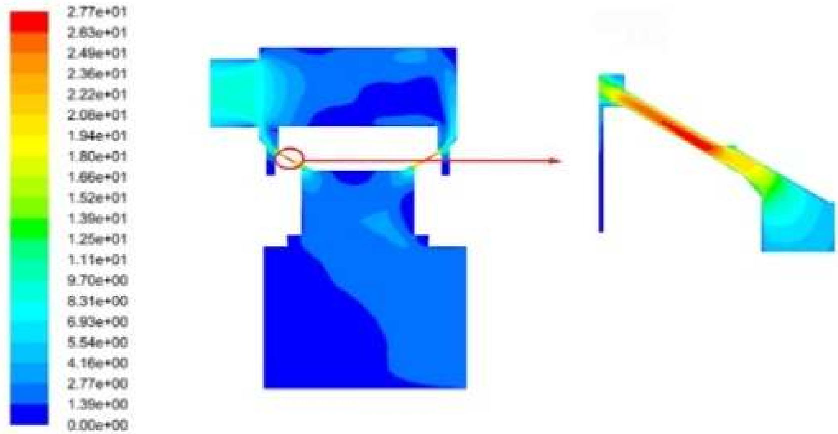


(a)Results of simulation analysis (b)Valve rubber failure

Fig. 5: Failure analysis and reliability validation

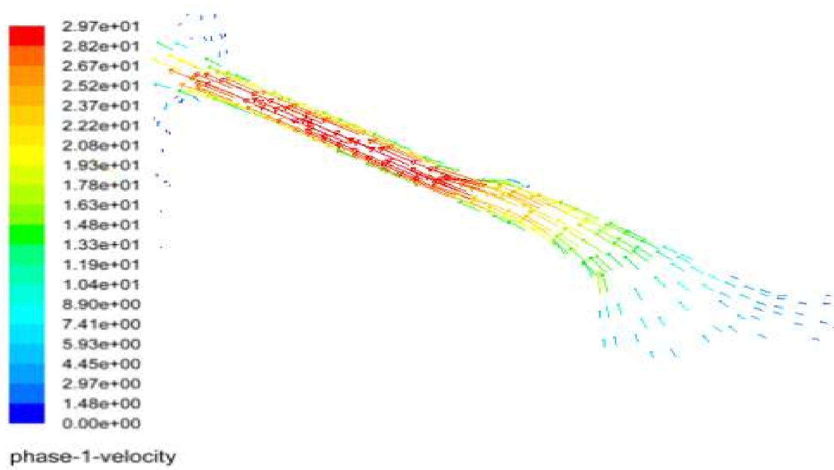


(a) Liquid

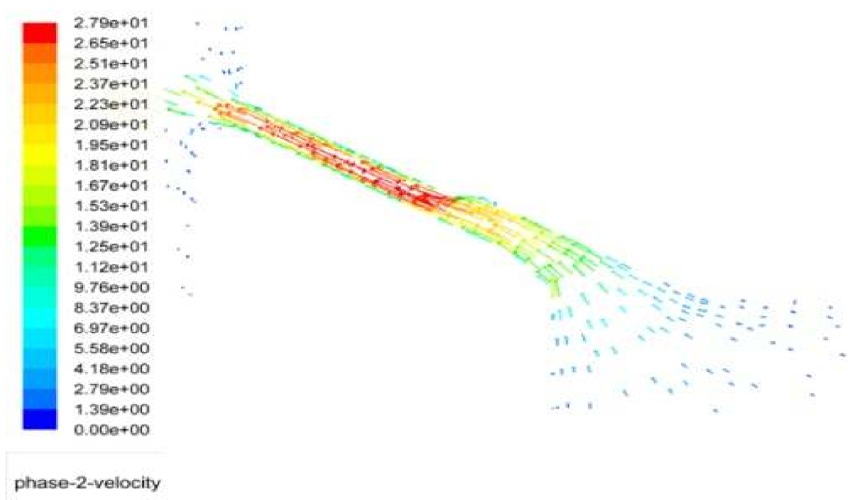


(b) Solid

Fig. 6: Solid-liquid two-phase velocity distribution at the gap



(a) Liquid velocity vector



(b) Solid velocity vector

Fig. 7: Solid-liquid two-phase velocity vector at the gap

Table 2: The maximum velocity of solid-liquid two-phase

Particle diameter (*μm*)	The maximum velocity of the liquid (*m/s*)	The maximum velocity of solid (*m/s*)
400	29.65	27.89
600	29.85	27.39
800	30.09	27.01

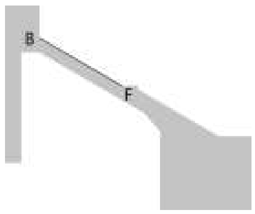


Fig. 8: Rubber near the wall BF

condition is shown in Fig. 5b. When the valve lift is 2.02 mm, the stroke is 400 r/min and the valve cone angle is 60°. Parts that produce erosive wear gather mainly in the contact between the rubber inner ring and outer ring of the valve seat, which is consistent with the site of field failure and indicates that erosion wear is one of the leading factors for failure. This proves that the numerical simulation method in this paper is reliable (Mo *et al*., 2016).

Velocity distribution of internal flow field in valve rubber: Figure 6 and 7 show results for a pump lift of 2.02 mm, punching at 400 r/min, the taper angle of 60°, the solid content of 20% of the working conditions at the gap at the solid-liquid two-phase velocity-distribution cloud and velocity vector. The velocity distribution of the solid phase is similar to that of the liquid period, but the value is slightly lower than that of the fluid velocity. The highest speed in the gap flow field occurs at the bottom because the valve rubber has a certain protruding thickness. This protruding thickness decreases the cross-sectional area of the flow channel through valve play suddenly and the flow velocity increases. The fluid velocity in the grooved runner after the valve rubber decreases because rising in an annular cross-sectional area of the gap length and a loss of energy in the flow.

Effect of particle diameter on flow field in rubber: Because the speed of the chute flow channel is much faster than that of the other parts of the valve, to analyze erosion wear of the valve rubber, the velocity distribution at the solid surface of the rubber wall and flow field data near the mortar wall were obtained. A parallel surface was formed at 0.02 mm from the rubber wall and the straight line BF is the intersection of the surface with a symmetry plane x = 0, as shown in Fig. 8.

Table 2 shows the maximum velocity of the solid-liquid two-phase in the play of the drilling pump valve for different particle diameters and pump valve conditions. The peak solid-liquid two-phase velocity in the flow field for different-diameter particles is similar and the maximum velocity in the gap at the bottom of the rubber obeys a specific law. A more massive particle diameter yields a greater maximum liquid velocity and reduces the maximum speed of the solid phase. When the particle diameter is doubled, the change in velocity is approximately one thirtieth. The change in velocity is small relative to the increase in diameter. The difference in particle diameter has little effect on the speed of the solid phase in the gap. Themaximum velocity change of the solid-liquid two-phase is small and the impact of erosion of the valve rubber is weak.

Effect of punching on internal flow-field velocity: As shown in Fig. 9, the solid-phase speed of the pump near wall BF is different from that of the sampling point. The trend in solid velocity in the near wall BF was consistent with that of varying punching. With an increase in punching, the solid-phase velocity of the next wall BF of the valve rubber increased gradually. When the Z direction of the position is higher than –0.047 m, the rubber wall of the solid-phase speed rises sharply. The rate was significantly higher than in the other locations, which indicates that erosion in these places yields more severe wear and tear. A punching of more than 450 times will cause poor fractured pump-valve pressure and a significant increase in the fracturing pump-valve flow rate. The increase in punching will exacerbate the eraser wear eruption and reduce the service life of the rubber.

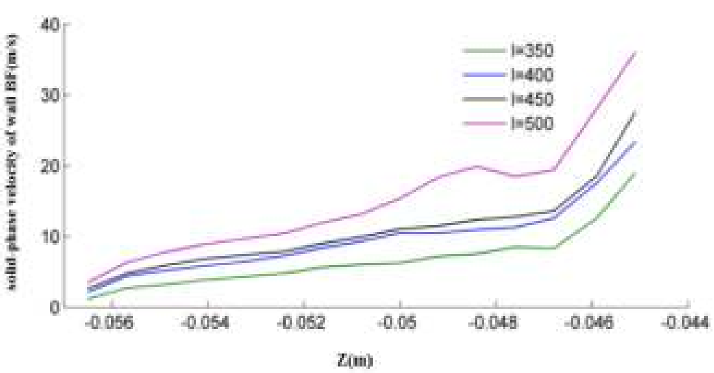


Fig. 9: The solid-phase velocity of pump wall near wall BF

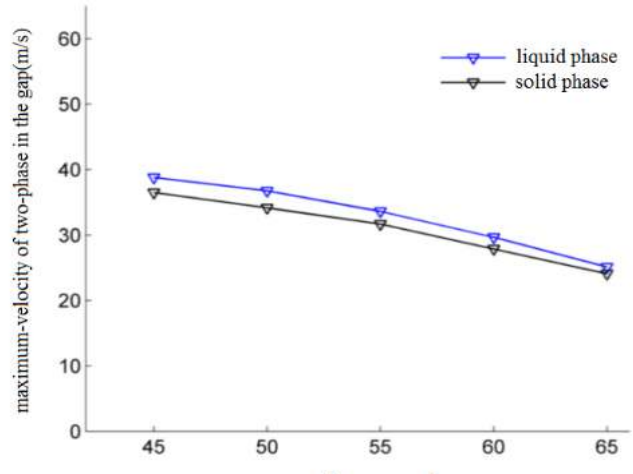


Fig. 10: The maximum velocity curve of solid-liquid two-phase in the gap

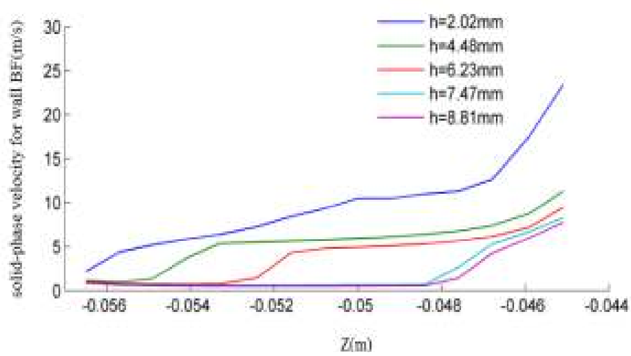


Fig. 11: Solid-phase velocity for different lifts near the wall BF

Effect of taper angle on flow field in rubber: As shown in Fig. 10, the change in maximum velocity of the solid-liquid two-phase in the gap is the same at different taper angles. With an increase in the valve cone angle, the velocity of the flow field through valve play decreases and the speed difference between the solid and liquid phases decreases. When the valve cone angle exceeds 55°, the speed of the solid-liquid two-phase is cut down more rapidly. In the valve body and valve seat-hole diameter, the valve cone angle increases the cross-sectional area of the basin and the cross-sectional area has a small local speed. Therefore, the flow rate of the valve gap is decreased and the erosion effect of the fracturing fluid on the valve rubber is reduced. An increase in taper angle of the valve can reduce the flow rate of the surface fluid of the valve rubber and improve the wear state of the valve rubber and the sand fracturing fluid and thus improve the service life of the valve rubber.

Effect of lift on the velocity of the internal flow field: As shown in Fig. 11, with an increase in lift, the solid-phase speed of the pump near the wall BF decreases and the trend in solid-phase velocity at BF is the same. For a Z-direction position more significant than -0.047 m, the rubber wall of the solid phase rate increased sharply, the speed was significantly higher than at other locations and it was a maximum at the bottom of the rubber, which indicates severe erosion. At h = 2.02 mm, the maximum velocity of the solid phase in the rear wall of the rubber reached 23.4 m/s. A maximum flow rate will be generated when the valve is opened and closed. At this time, the eruption is most dangerous. As the lift decreases, the cross-sectional area of the basindecreases, the velocity of the plug flow adds and the erosion effect of the fracturing fluid on the valve rubber increases.

CONCLUSION

The study of the solid-liquid two-phase flow yielded the velocity distribution near the internal flow field and the Velcro rubber in the valve gap. The erosion performance of the pump rubber for different working conditions and various structural parameters were estimated and is summarized as follows:

- With an increase in the solid content in the fracturing fluid, the maximum turbulent kinetic energy at the gap increases, the concentration of sand at the bottom of the rubber increases and the erosion wear is more dangerous.
- When punching increases, the natural rubber wall near the BF wall of the solid-phase speed increases, which increases the erosion of the eraser rubber wear.
- With an increase in taper angle of the pump valve, the velocity of the flow field through vale play decreases and the speed difference between the solid and liquid phases decreases. For a taper angle greater than 55°, the speed of the dual solid-liquid phase decreases significantly. Thus, to reduce the valve-rubber erosion, a more significant taper angle can be chosen.
- With an increase in lift, the solid-phase velocity of the pump wall near the wall is reduced and the fracturing fluid is weakened.
- The change in particle diameter has little effect on the velocity of particles in the gap and low impact on valve-rubber erosion.

Therefore, to reduce pump-rubber erosion failure, the pump structure can be improved and the structural model of the pump angle and the lift can be increased.

ACKNOWLEDGMENT

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CONFLICT OF INTEREST

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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