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Research paper

Fluid–solid coupling simulation of a new hydraulic self-adaptive PDC cutter for improving well-drilling efficiency in complex formations

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ABSTRACT

A new type of hydraulic self-adaptive polycrystalline-diamond-compact (PDC) cutter (SAPC) is designed for controlling cutting depth of the PDC bit flexibly and reducing the harm of stick–slip vibration to drilling operation. The fluid–solid coupling movement of SAPC under different well-drilling conditions are simulated and analyzed. The results show that the up-going time of SAPC can be increased by reducing the diameter of the thin connecting pipe, increasing the diameter of the SAPC liquid-cavity, increasing the height of the cavity, increasing the liquid viscosity and increasing the initial spring force/decreasing the elasticity coefficient. Among them, reducing the diameter of thin connecting pipeline and increasing cavity diameter are the most sensitive. The up-going time can also be increased by the way of changing liquid viscosity without changing the structure of SAPC. Increasing the initial spring force and decreasing the elasticity coefficient can also increase the up-going time of the SAPC, however, the response window to the linkage force is reduced. The double-pipeline embedded SAPC can effectively reduce the volume and installation difficulty. The reasonable thin pipeline diameter is 0.2–0.5 mm, and the thick pipeline diameter is more than 2 mm, and the cavity diameter is more than 18 mm. Based on the results of the numerical simulation study, the up-going time of the SAPC is designed over 1.25 s, which meets the performance requirements of the hydraulic SAPC using in complex reservoir drilling, such as carbonate-sandstone reservoir.

0. Introduction

PDC bits are the main drilling equipment in oil and gas exploration and development. More than 85% of oil and gas well drilling task in my country is completed by PDC bits (Jain et al., 2016; Kenneth and Russell, 2016; Zhang et al., 2018). The overall improvement of drilling efficiency and life span is essential for reducing production costs, improving economic benefits, and improving the technical level of exploration and development equipment. Ensuring national energy security is of great significance. In the process of drilling in deep complex formations, downhole drilling tools often exhibit complex motion states, such as lateral, axial and circumferential motion, among which stick–slip vibration is one of the most common forms, which was first discovered in the 1980s (Iii et al., 2013; Schwefe et al., 2014).

Stick–slip vibration is manifested as periodic harmful motion where the bottom hole stops rotating and high-speed rotation alternates back and forth. In 2010, Ledgerwood pointed out that stick–slip vibration is an important cause of PDC bit damage, which will accelerate drill tool fatigue failure, reduce drilling efficiency, threaten engineering safety, and cause economic losses. The bit is the main factor causing stick–slip vibration. The bit has penetrated the rock too deep, and the bit torque is not enough to break the larger rock unit (Jain et al., 2011; Selnes et al., 2008; Livescu et al., 2017; Livescu and Watkins, 2014). At this time, the bit stops rotating and enters the viscous stage; the upper drill string continues to rotate and accumulate energy, and the torque continues to accumulate until the rock is broken, and the bit rotates with high-speed and enter the slippage phase (Li et al., 2020; Si et al., 2017; Chen et al., 2017; Pastusek et al., 2018).

The control of cutting tooth penetration depth is the key to solving stick–slip vibration. The main measures include improving the structure of the drill bit and increasing the downhole sub-sections. In 2011, Baker Hughes developed a fixed limit gear bit, but at the cost of reducing the drilling rate, the application effect was limited. In 2017, Baker Hughes released the first industrial adaptive drill-TerrAdapt (Izbinski et al., 2015). The difference of this bit is that there is an adjustment device on the bit, which can automatically adjust the cutting depth of the bit according to

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the conditions of the formation rock, reduce the vibration, stick–slip and the impact of the formation on the bit during drilling, and improve the drilling speed. Traditional PDC drill bits can only be designed for a particular kind of rock (Xu et al., 2017). In the actual drilling process, the drill bit often needs to penetrate many different types of rock layers. Therefore, the traditional PDC bit drills from one type of rock to another. In the process, the drill bit will produce stick–slip due to vibration, and the drill bit may stop rotating due to the cutting too deep and get stuck in the rock, while the drill rod continues to rotate, resulting in accelerated wear of the drill bit and even equipment damage. The adjustment device installed on the TerrAdapt drill bit can automatically adjust the cutting depth according to the specific conditions of the formation and reduce the vibration of the drill bit during drilling (Ning et al., 2017). It can also absorb the sudden impact on the drill bit surface and reduce the damage to the drill bit and other downhole equipment. After trial use of this drill bit in the Delaware Basin of the United States, the drilling speed increased by 27% compared with the average drilling speed in the area. The drill bit reduces 90% of the torque vibration, which proves that it greatly reduces the stick–slip when the drilling (Negm et al., 2016; Abdila et al., 2018; Crane et al., 2017; Gumich et al., 2017).

PDC bits are important rock-breaking tools in the fields of oil-gas, geotherm, geology and construction engineering. At present, nearly 90% of drilling footage in the world is obtained by PDC bits, which bring significant comprehensive economic benefits. With the well depth increasing, the rock hardness increases, the plasticity and the formation heterogeneity strengthens, the drill-ability worsens, and the geological time and geological conditions of drilling are complex. Under the condition, PDC bit cutting depth fluctuates, resulting the fluctuation of bit torque and rotation speed aggravation (Hurlburt et al., 2019; Chowdhury et al., 2019b; Niu et al., 2018). In other words, PDC bits produce stick–slip vibration, which reduces the crushing capacity of the bit. Stick–slip vibration can be self-sustaining and occur continuously with drilling operations.

The stick–slip vibration of the PDC bits brings serious hazards to drilling operation, which are mainly reflected in the following aspects (Yang et al., 2016; Brett et al., 1990; Chowdhury et al., 2019a; Tang et al., 2018; Elsayed and Raymond, 2002):a. It is difficult to apply the bit pressure evenly on the bit, which makes the bit keep leaving and hitting the bottom hole, accelerating the bit wear and advancing impact damage of the PDC bits ; b. Reducing the drilling continuity and the wellbore quality will lower the rock breaking efficiency; c. Periodic torque load leads to fatigue failure of the drill strings; d. The tool face control difficulties will affect the directional ability of the directional drilling system. PDC bit stick–slip vibration mechanism is sophisticated. The mainstream industry view of the main stick–slip vibration causes mainly include (Greg et al., 2014; Mensa-Wilmot and Alexander, 1995; Huang et al., 2018; Hui et al., 2019): a. The friction between the drill strings and the wellbore; b. The velocity attenuation effect between the drill bits and the rocks; c. The coupling effect of axial vibration and torsional vibration within drilling tools. The range of optimized drilling parameters that is increasing drilling speed and reducing the required amount of energy for drilling formation (Davarpanah et al., 2018; Zhu et al., 2020; Davarpanah and M.M., 2016). The method of applying the SAPC on PDC bits to control the cutting depth has been widely accepted. Based on this, a new-type bit with cutting tooth that can adaptively control penetration depth is presented.

1. Structures and working principles of the new SAPC

The schematic diagrams of PDC bit and SAPC are shown in Fig. 1. The working principle of the new SAPC is shown in Fig. 2. The SAPC mainly consists of four parts, which are, a hydraulic cavity, two circulation pipelines, a piston and a connecting rod. The piston is placed in the hydraulic cavity, and the hydraulic cavity is divided into the upper cavity and lower cavity. These two cavities are filled with hydraulic oil or lubricating oil. The piston is connected or fixed to the cavity wall by springs. The two circulation pipelines are placed outside the hydraulic cavity or with the piston opening holes, connecting the two cavities respectively. And the two pipelines are respectively installed with one-way valve and have different inner diameters. One end of the connecting rod connected with the piston, and the other end connected with the SAPC which is placed behind the cutting tooth of the bit. In the off-working state, the piston is clinging or close to the lower wall of the cavity under the force of the balance force between the spring and the fluid in the cavity. When the piston reciprocating movement as mentioned above happens in the hydraulic cavity, the volume of the upper and lower cavities changes constantly, and the fluid in the cavity flows between the two cavities through the two circulation pipelines as stated. Two circulation pipelines are installed with one-way valves or similar devices, making the left side as the upper circulation pipeline 4 while the right side as the lower circulation pipeline 3.

The two circulation pipelines as stated have different inner diameters with the size of d1 and d2 respectively ($d1 > d2$), which makes the fluid velocity different within the two pipelines and the reciprocating movement velocity of the SAPC driven by the piston different under the same conditions. In the lower cavity, the fluid flows through the ascending circulation pipeline 4 by velocity V1 into the upper cavity, while the fluid flows through the ascending circulation pipeline 4 by velocity V2 into the lower cavity in the upper cavity ($V1 > V2$). The SAPC driven by the piston to move up in velocity V1 and move down in velocity V2 ($V1 < V2$). The SAPC is preinstalled in the bit. According to the position of the SAPC, the connecting rod as stated is made into a straight rod or a set of mechanical transmission device.

The core is the control unit of the SAPC. To validate the feasibility of the structure, the method of numerical simulation is planned to be used in preliminary design and parameters verification of the control unit, as well as the optimization of the position relationship with the bits, in order to obtain a reasonable unit design which satisfy conventional drilling confining pressure downhole and the operating conditions such as drilling pressure. It lies a theoretical foundation for field practice to design a new type of bit, control PDC bit penetration depth, restrain PDC bit stick–slip vibration and increase the rock-breaking efficiency. It is of great practical significance to promote the steady development of the oil well drilling overseas.

In Fig. 2, 1. Hydraulic cylinder, 2. SAPC cavity, 3. Down circulation pipeline, 4. Up circulation pipeline, 5. Piston, 6. Connecting rod, 7. Upper cavity, 8. Lower cavity, 9. Liquid, 10. Lower flexible assembly, 11. Down-going one-way valve, 12. Up-going one-way valve, 13. gear, 14. Cutting gear, 15. Upper flexible assembly.

2. Turbulence model and dynamic grid by UDF

2.1. Turbulence model

Turbulence phenomenon exists widely in nature and engineering applications. When the piston of the SAPC moves up and down, the disorderly and unsystematic state occurs in the fluid of the inner SAPC due to the instable moving velocity and the complex structure inside of SAPC. Some vortices of different sizes

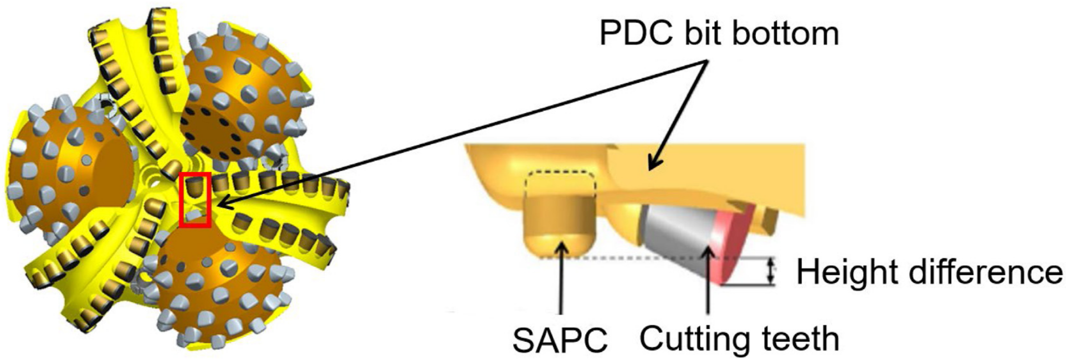


Fig. 1. PDC bit and SAPC.

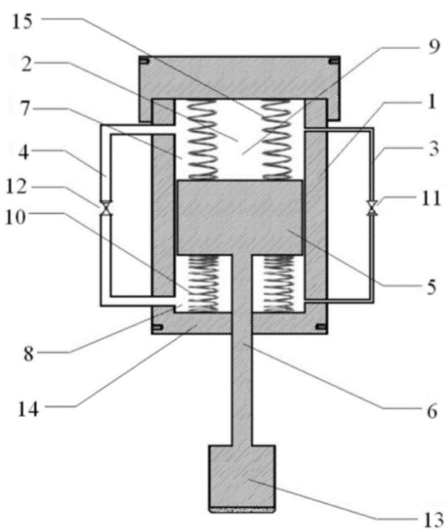


Fig. 2. Schematic diagram of the new type of SAPC.

may be generated largely, and randomness lies in the rotation axis direction of the vortex. Some of the large vortices are getting smaller due to the disturbance among vortices or other reasons. The small vortex dissipated and disappeared due to the viscidity of the flowing liquid. While the disturbance made by the boundary of mainstream regenerates the vortices of different sizes. Such a reciprocating process is essentially the transformation of mechanical energy and thermal energy. In such a flow system, physical quantities such as velocity and pressure have strong pulsation, which is the turbulence.

Theoretically, there is no need to add other equations when solving the N-S directly. It can be directly solved by the flow system with turbulence, but this way is rather difficult. Nowadays, the computer hardware facilities can hardly achieve the large-scale computation. So, the turbulence in the flow system increases the difficulty of solving the control equation. Hence, the researchers begin to put up with a computing method specifically for turbulence. The basic idea is to perform the physical quantities with time-averaged process in order to reduce computer expenditure. This approach has led to the emergence of many turbulence models. During the flowing process of the fluid, due to the presence of viscosity, there is an interaction force between each layer of fluid, resulting in the interaction between each layer of fluids. Fluid flows irregularly. This flowing state is called turbulent flow. The Reynolds number (***Re***) is the most important characteristic parameter of the fluid. The range of its value can be used to judge the state of the fluid,with the symbol of ***Re*** as follow.

$$Re = \frac{pvL}{\mu} \tag{1}$$

where, ***L*** represents characteristic size. The physical meaning is expressed as the ratio of inertial forces to viscous forces. When the value of ***Re*** is greater than a reference value, the flow of fluid becomes turbulent flow. When the value of ***Re*** is smaller than the reference value, the flow of fluid is laminar flow. The existence of eddy current superposition of different sizes in turbulent flow is the characterization of fluctuation velocity.

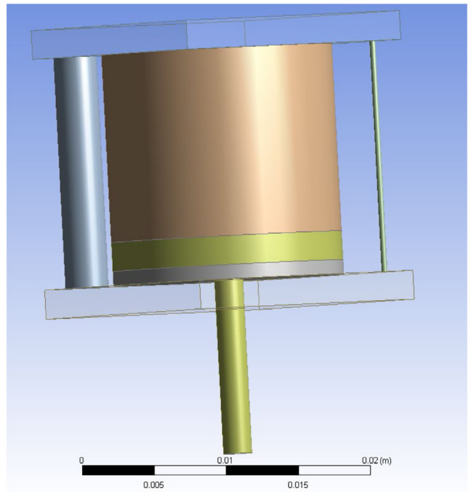
In CFD simulation, the selection of the turbulence model will vitally affect the solved results. The direct numerical simulation method, large eddy simulation model and average equation based on ***Re*** are much frequently used in engineering. The application ranges are variable according to different turbulence models with different ***Re***. Most simulation depends on the ***Re*** average equation. The other two turbulence models need further consideration of grid accuracy requirements and rationality of the calculation cost requirements.

At present, according to the traditional classification method, there are eddy viscosity sealing mode and Reynolds stress mode in the Reynolds average N-S turbulence equation of CCM+. According to the usage of different turbulence models and the characteristics of SAPC unit, the second equation based on the eddy viscosity sealing mode will be chosen. According to the requirement of the fluid flow condition and the computing resource requirement, as well as the good compromise by different processes such as calculation robustness, accuracy and lower computational cost, etc. It is rather suitable for complex industrial application, the k-Epsilon model is usually chosen as the turbulence model for CFD study.

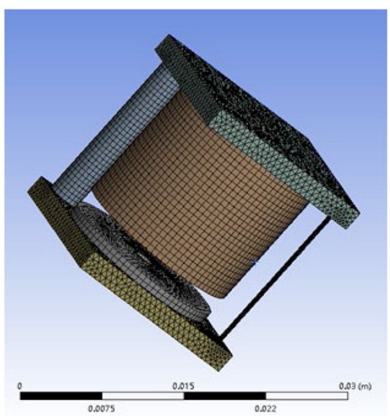
The standard K-Epsilon model is widely used. In comprehensive consideration of the characteristics of the SAPC control unit, as well as the flow characteristics and the model complexity, etc., the standard K-Epsilon model of the two-equation model is adopted in this model.

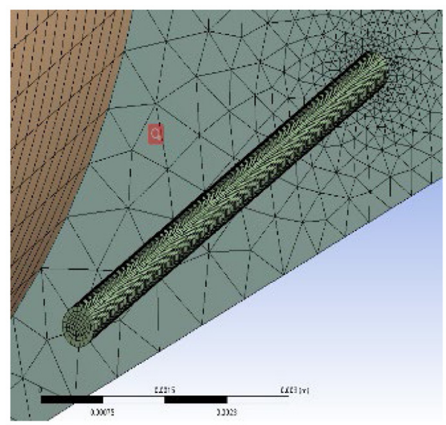
2.2. The flow field calculation equation of constant-type dynamic grid

In the process of simulation with dynamic grid technology, the movement rule of moving boundary can be according to the movement rule that is set in advance (linear velocity and angular velocity), which is called active dynamic grid. Also, can after each time step, the movement rule of the current calculating time boundary can be solved by Euler method with the solved flow field parameter, which is called passive dynamic grid. The two grids update according to the dynamic grid updating method and the movement rule.



a. SAPC 3D model





b. Grids of liquid region c. Local mesh refinement near the thin rod

Fig. 3. SAPC 3D model and grids of liquid region by finite element method.

Table 1
Parameters and initial values for SAPC numerical simulation.

Parameters	Initial values
Cavity height	16 mm
Connecting rod diameter	2 mm
Spring coefficient	150 N/mm
Designed route	6.6 mm
Simulated temperature	100 °C
Piston diameter	16 mm
Connecting rod force	2500 N
Initial spring force	1500 N
Hydraulic oil density	872 kg/m^3
Initial installed place	1 mm
Thin connecting pipeline diameter	0.4/0.2 mm
Thick connecting rod diameter	3 mm
Hydraulic oil elastic modulus	1500 MPa
Hydraulic oil viscosity	5.6 mm^2/s

In the computing region of dynamic grid, the governing equation in the integral form of arbitrary scalar ϕ in the arbitrary control body V can be expressed as:

$$\frac{d}{dt}\int_V \rho\phi dV + \int_{\partial V} \rho\phi(\vec{u}-\vec{u}_g)\cdot d\vec{A} = \int_{\partial V} \Gamma\nabla\phi\cdot d\vec{A} + \int_V S_\phi dV \quad (2)$$

where, ρ is the fluid density, $\vec{u}$ is the vector of the fluid velocity, $\vec{u}_g$ is the velocity of the dynamic grid, Γ is the dissipation coefficient, $\vec{A}$ is normal vector of the face A, S_ϕ is the source term of ϕ, t is the time step, ∂V is the boundary of the control body V.

The derivative term with respect to time in Eq. (2) can be written as a first-order difference form:

$$\frac{d}{dt}\int_V \rho\phi dV = \frac{(\rho\phi V)^{n+1} - (\rho\phi V)^n}{\Delta t} \quad (3)$$

n and $n+1$ respectively represent the current and the next moment. The control body V^{n+1} can be solved by the following equation:

$$V^{n+1} = V^n + \frac{dV}{dt}\Delta t \quad (4)$$

where, $\frac{dV}{dt}$ is the derivative of the volume of the control body with respect to time. In order to satisfy the grid conservation law, $\frac{dV}{dt}$

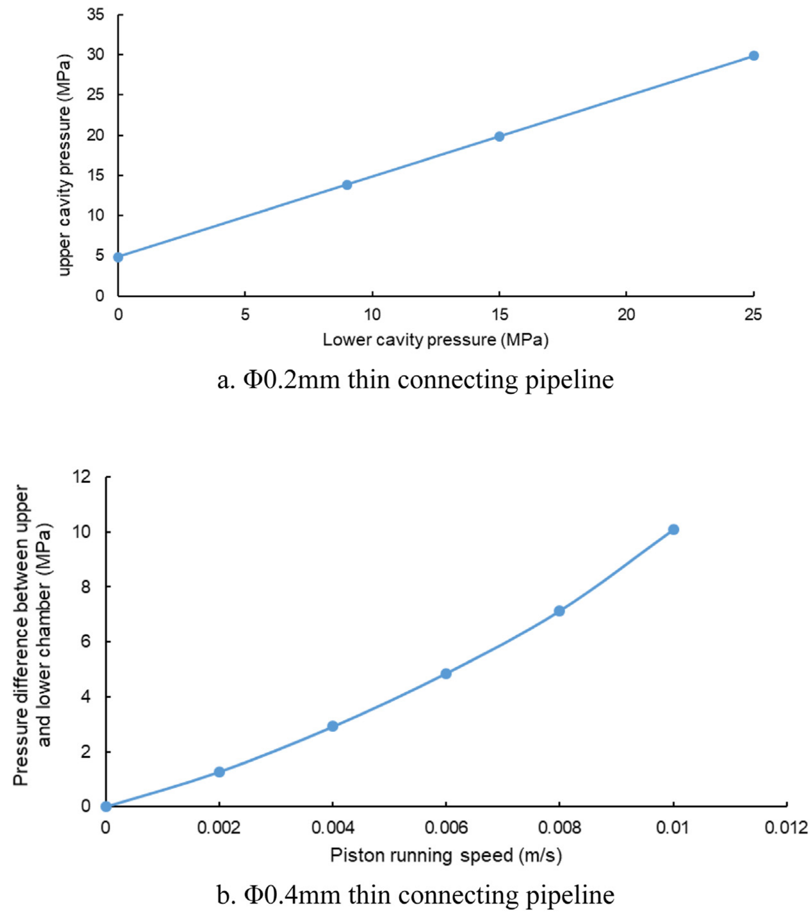


Fig. 4. The pressure in the upper and lower cavities and piston movement velocity of different thin connecting pipeline diameters.

can be obtained by solving the following equation:

$$\frac{dV}{dt} = \int_{\partial V} \vec{u}_g \cdot d\vec{A} = \sum_j^{n_j} \vec{u}_{gj} \cdot \vec{A}_j \tag{5}$$

where, n_j represents the number of the faces of the control body, and $\vec{A}_j$ represents the normal vector of the face j. The dot product $\vec{u}_g \cdot d\vec{A}$ of any surface of the control body can be obtained by solving the following equation:

$$\vec{u}_g \cdot d\vec{A} = \frac{\delta V_j}{\Delta t} \tag{6}$$

where, δV_j is the volume formed by scanning the j surface of the control body in the time step of Δt.

We use FLUENT to calculate the fluid flow characteristics and pressure distributing field of the SAPC pipeline and cavity, and then solve the dynamics and kinematics equations of linear movement of the piston with the user-defined function (UDF), obtaining piston displacement and displacement variation for each time step. Cooperated with the dynamic grid to regenerate computing grid of the entire flow field, repeatedly, and eventually the movement condition of the piston in the whole flow field and a more actual simulation flow field will be obtained. At the same time, user-defined functions are also used to load the pressure and the boundary of the liquid's physical property parameters. Then, the density and pressure changing with the variation of the cavity volume would be realized.

3. SAPC movement simulation and analysis

3.1. SAPC model, grids and parameters

The external double tube model is a common structure of the SAPC and a referable structure in current engineering applications. It has simple structure but large volume. In order to find out the influence of the structure details on the piston movement characteristics, we made a detailed numerical parameter analysis on the external tube model. The SAPC numerical model and grids are shown in Fig. 3. A total of 8 parameters are analyzed, which include thin connecting pipeline diameter, cavity diameter, cavity height, liquid viscosity, liquid elastic modulus and spring performance. In order to analyze the simulation process well, the basic parameters of the model are set in this paper as shown in Table 1. In order to ensure the validity of the data comparison results, the grid side length is used to control the number of generated grids. When analyzing the parameters, only the value of the analyzing parameter keeps changing, but the other parameters remain unchanged.

3.2. Thin connecting pipeline diameter analysis

The thin connecting pipeline diameter is the core parameter of the whole structure. The up-going velocity and time of the connecting rod piston are controlled by the throttling effect of the thin connecting pipe. It can meet the requirements of the SAPC for different hardness strata and effectively eliminate or weaken the occurrence of stick–slip vibration of the bits and the drilling tool. In this paper, the flow in the thin connecting pipeline is described

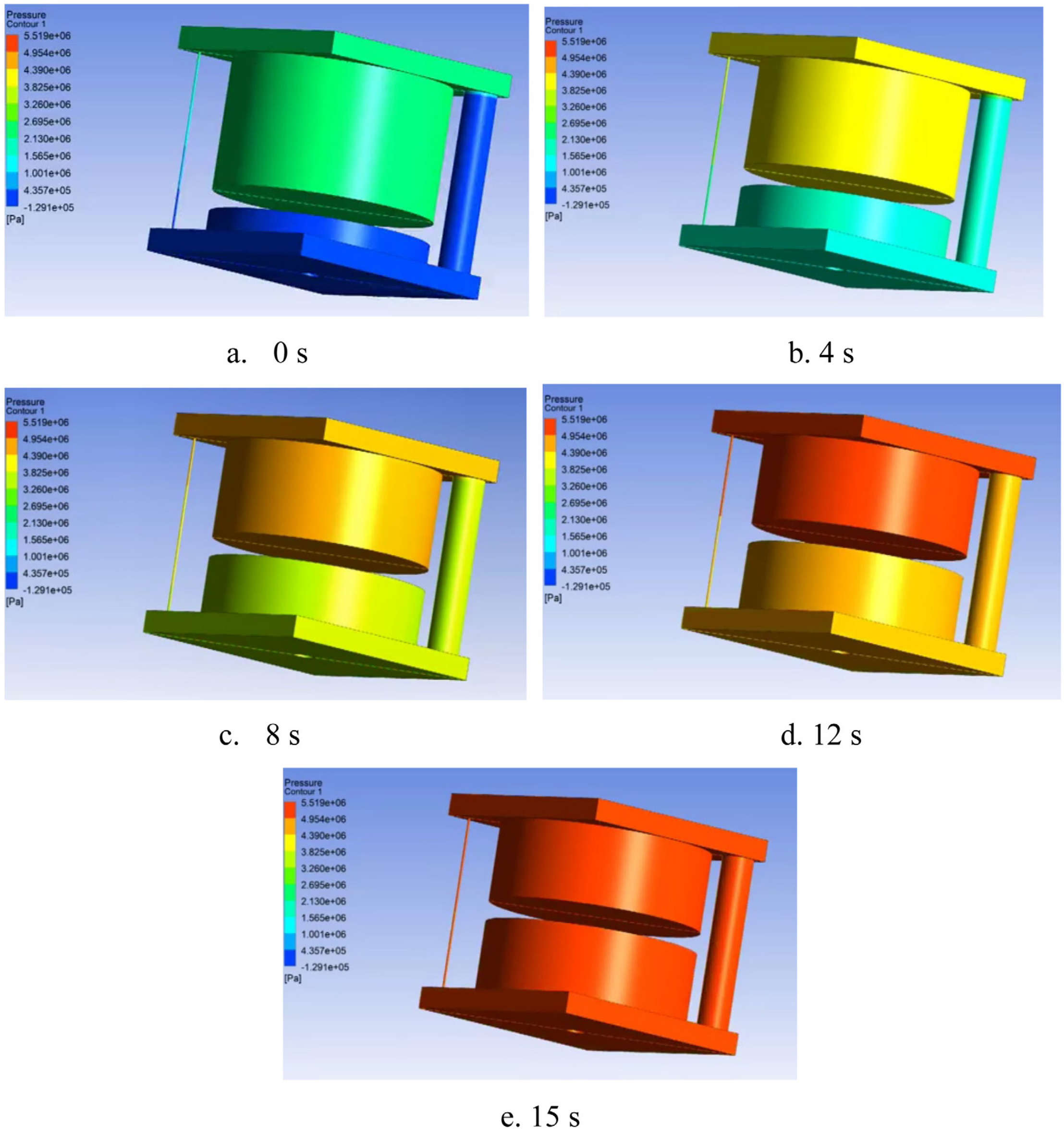


Fig. 5. The cloud diagrams of upper and lower chamber pressures at different time.

and analyzed in detail by simplifying the SAPC structure model, which provides parameter data for the later model structure design. The variation of the flow velocity with the changing pressure of the lower cavity by the thin pipeline diameter of 0.4 mm and 0.2 mm respectively is analyzed, as shown in Fig. 4. The cloud diagrams of upper and lower chamber pressures under Φ0.2 mm thin connecting pipeline at different time are shown in Fig. 5.

The flow velocity increases with the increase of the upper cavity pressure while decreases with the decrease of the thin connecting pipeline diameter. The thin connecting pipeline should be determined comprehensively according to the sophisticated machining process and the SAPC movement requirements. When the thin connecting pipeline diameter is 0.4 mm, the pressure difference between the upper and lower cavities is small, while when the thin connecting pipeline diameter is 0.2 mm, the throttling effect caused by friction is more obvious, and the pressure difference between the upper and lower cavities is obviously higher.

3.3. Liquid cavity height analysis

The cavity height is one of the main parameters in the design of SAPC structure. In order to understand the influence of cavity height on piston movement, four structures with 12 mm, 16 mm, 20 mm and 24 mm cavity heights are designed for mathematical modeling analysis in this paper. The analysis results are shown in the figures below (Figs. 6–9).

The cavity height is one of the most important parameters in the design of SAPC, which determines the installation space and machining difficulty. But according to the results of numerical simulation, the cavity height has less influence on the piston movement characteristics. When the thin pipeline diameter is 0.2 mm, the maximum up-going time difference is 1 s between the cavity height of 12 mm and 24 mm. When the thin pipeline diameter is 0.4 mm, the up-going time difference is 0.1 s between the cavity height of 12 mm and it of 24 mm. The up-going time difference is mainly caused by the pressure changes in the cavity. According to the feasibility analysis of the models, more pressure changes will generate in the small cavity volume, increasing the pressures in the upper and lower cavities and the flow rate

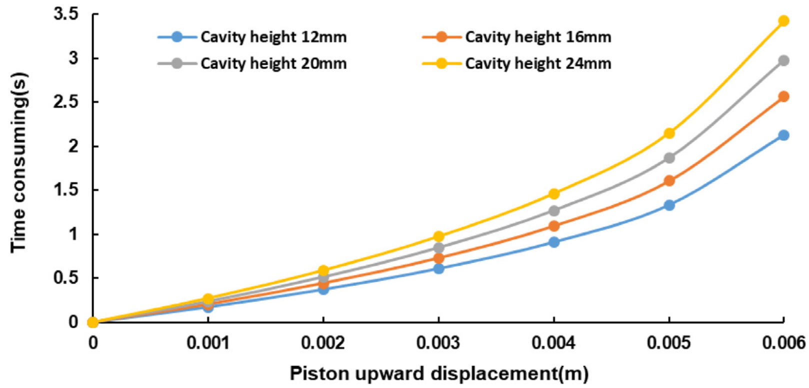


Fig. 6. The up-going displacement at different cavity heights under Φ0.2 mm connecting pipeline.

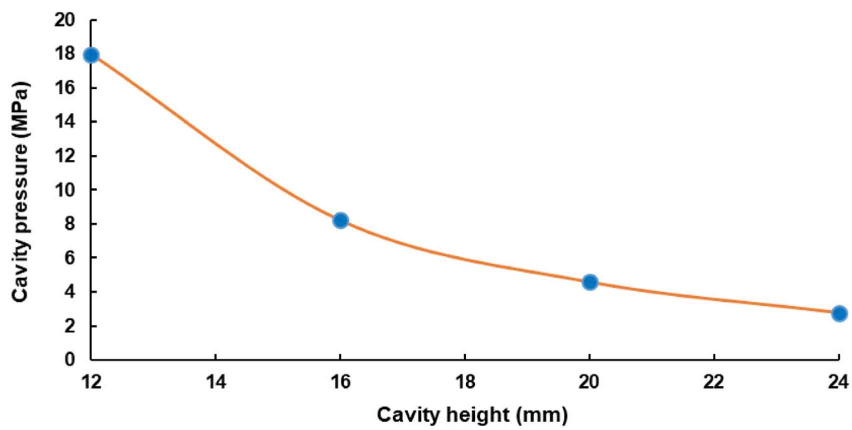


Fig. 7. The relationship between the cavity pressure and cavity height under Φ0.2 mm connecting pipeline.

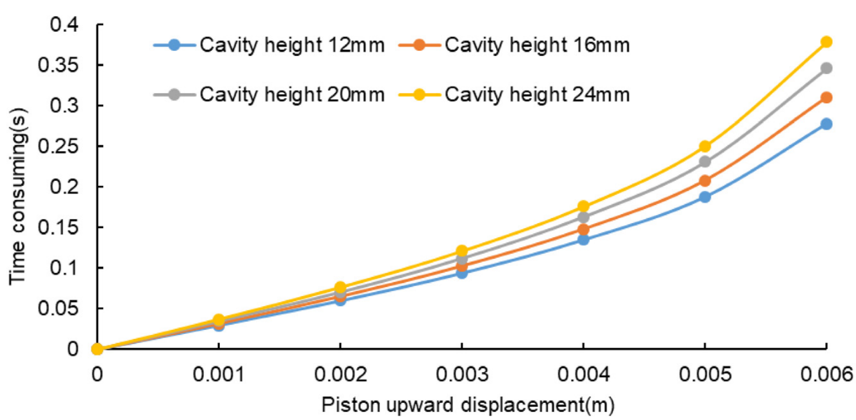


Fig. 8. The up-going displacement at different cavity heights under Φ0.4 mm connecting pipeline.

through the pipeline, which reflect the up-going time decrease accordingly.

3.4. Liquid viscosity analysis

Viscosity is a characterization of its internal friction by the dynamics of the fluid. The greater the internal friction and the molecular weight are, as well as the more hydrocarbon bonding, the greater the force will be. Also, there are more friction indenter loss under the same conditions. Viscosity is of decisive significance to various lubricating oils, quality identification and usage determination, as well as the combustion performance and consumption of various fuel oils. Taking the viscosity of the lubricating oil No. 32 at 100 degrees as the reference viscosity, the piston movement characteristics of the reference viscosity, 2 times the viscosity, 3 times the viscosity and 4 times the viscosity are analyzed. The calculated results are shown in Figs. 10–13.

By the analysis above, the liquid viscosity is known as one of the factors affecting the movement characteristics of the SAPC piston. High liquid viscosity can increase the flow resistance of the liquids, and reduce the up-going velocity of the piston, and improve the up-going time to some extent. The smaller the diameter of the thin pipeline is, the more obvious this effect will be.

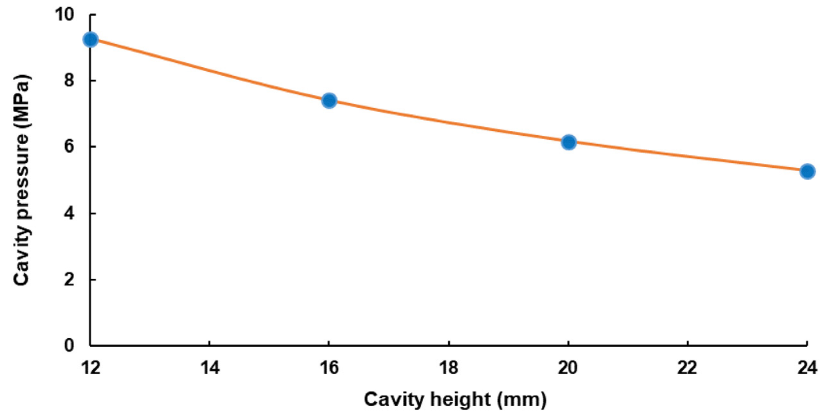


Fig. 9. Cavity pressure difference at piston maximum displacement with different cavity height under Φ0.4 mm connecting pipeline.

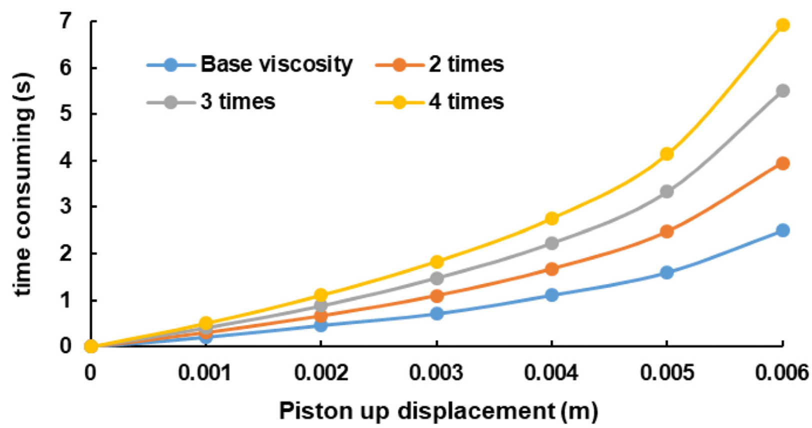


Fig. 10. The up-going displacement of different viscosity with Φ0.2 mm thin pipeline diameter.

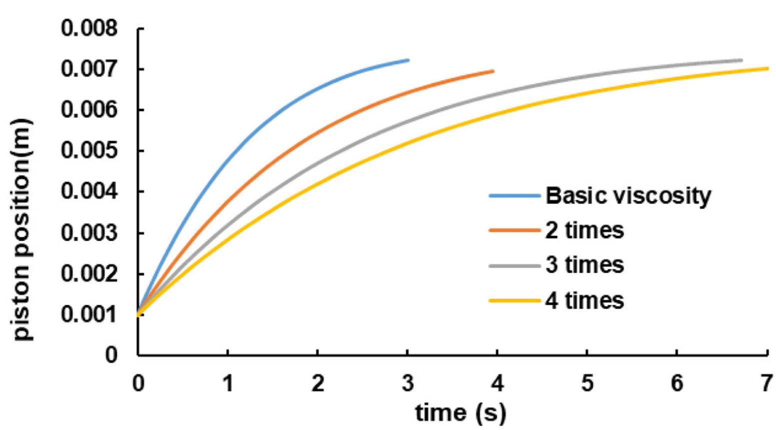


Fig. 11. The up-going position of different viscosity with Φ0.2 mm thin pipeline diameter.

3.5. Initial elastic force and elastic coefficient of spring analysis

Under the condition that the other parameters of the limit tooth piston remain unchanged, the initial elastic force and elastic coefficient of the spring are analyzed.

As shown in Figs. 14 and 15, the smaller the initial elastic force, the higher the upward speed of the piston, and the shorter the time it takes for the same displacement. The final stroke and cavity pressure changes have nothing to do with the spring starting elastic force and elastic coefficient.

4. Conclusion

The up-going time of the SAPC can be increased by reducing the thin connecting pipeline diameter, the cavity diameter, the cavity height, the liquid viscosity and the initial spring force/decreasing the elastic coefficient. Among them, decreasing the thin connecting pipeline diameter and increasing cavity diameter are the most sensitive. The up-going time can also be increased by the way of changing the liquid viscosity, without affecting the structure of SAPC. Increasing the initial spring force/decreasing the elastic coefficient can increase the up-going time of the SAPC, but the response window width of the connecting rod force will be decreased.

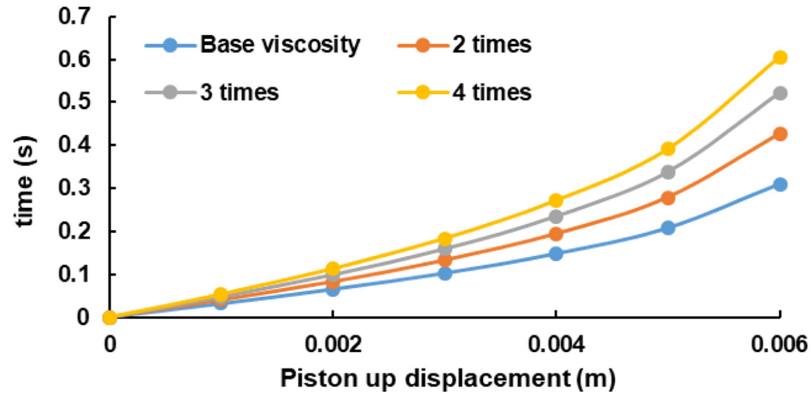


Fig. 12. The up-going displacement of different viscosity when the thin pipeline diameter is 0.4 mm.

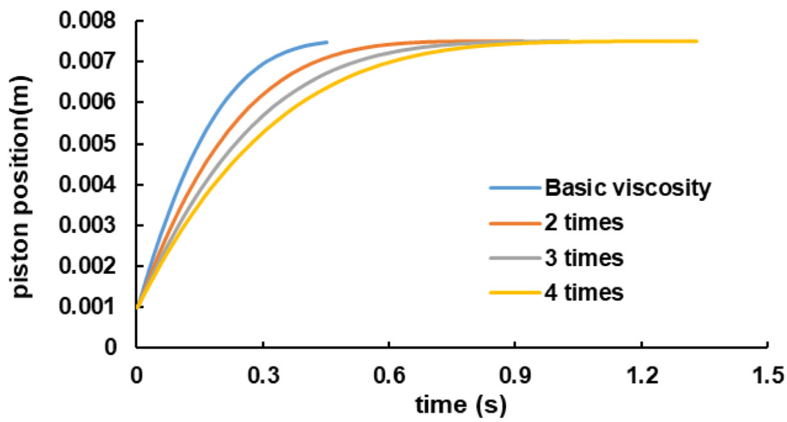


Fig. 13. The up-going position of different viscosity under thin pipeline diameter 0.2 mm.

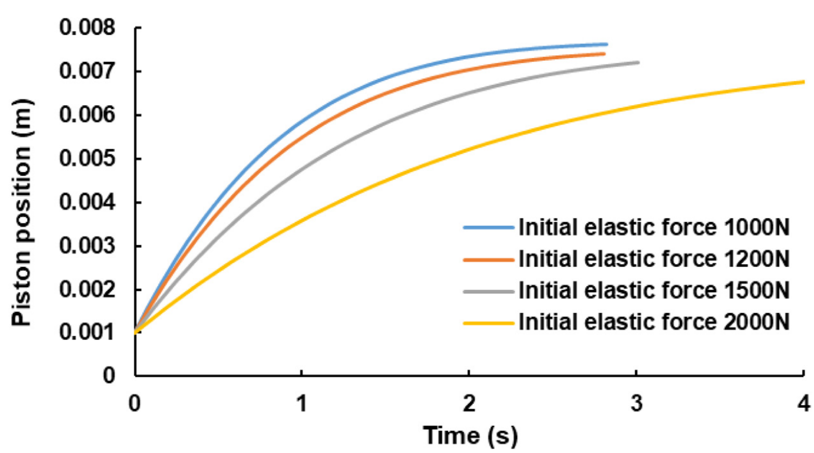


Fig. 14. The up-going displacement of different initial spring forces when the thin pipeline diameter is 0.2 mm.

The double-pipeline embedded model can effectively reduce the appearance volume of the model and reduce the difficulty of installation. The reasonable diameter of the thin tube is between 0.2–0.5 mm, the diameter of the thick tube is more than 2 mm, and the cavity diameter is more than 18 mm. The SAPC designed based on the results of the numerical simulation research of this project takes about 1.25 s to move upward, which basically meets the performance requirements of the limit gear. By controlling the expansion and contraction of the SAPC and the height difference with the PDC cutter, the depth at which the drill bit enters the rock during drilling is optimized.

Speaking of application prospect, first of all, this problem of stick–slip has been detected in well drilling all over the world, it is a universal problem. Second, it can save time and costs once the problem is eliminated or even relieved. Therefore, we believe that the SAPC and the anti-stick–slip PDC bit have profound application potential in developing the ultra-deep and unconventional reservoirs, especially in this era shocked by low oil price and the pandemic. All these make the research increasingly attractive and promising.

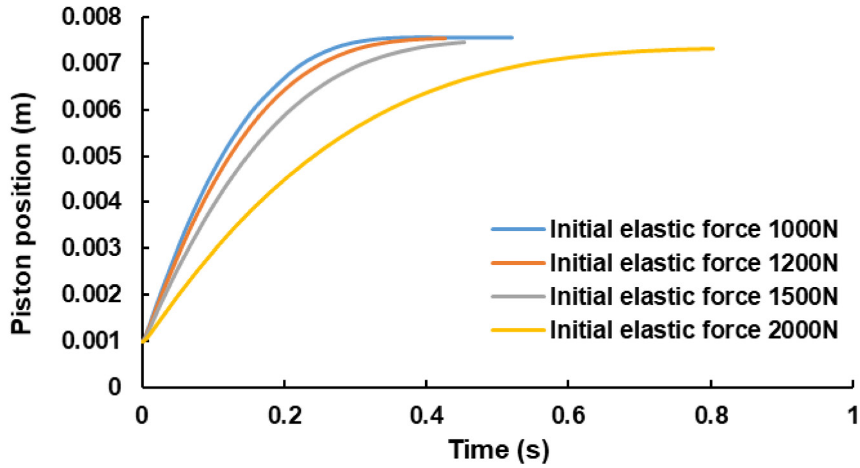


Fig. 15. The up-going displacement of different initial spring forces when the thin pipeline diameter is 0.4 mm.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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