International Journal of Latest Engineering and Management Research (IJLEMR)
ISSN: 2455-4847
www.ijlemr.com || Volume 06 - Issue 06 || June 2021 || PP. 61-70

Cementing displacement law of eccentric annulus at different well inclination angles

Haodong CHEN[1], Zhonghan YANG [1], Wentuo LI [1], Shuangjin ZHENG[2*]

[1]*(Zhanjiang Branch of CNOOC (China) co. LTD, China)*

[2]*(School of Petroleum Engineering, Yangtze University, China)*

Abstract: In order to study the displacement mechanism of eccentric annulus at different well deviation angle and to improve displacement efficiency, numerical simulation was carried out for cementing process at different well deviation angles, density difference between displacement fluid and displaced fluid and displacement velocities, and the displacement rules and the optimization direction of displacement efficiency under different conditions were obtained. The results show: under the same well deviation condition, the cementing displacement efficiency generally increases with the increasement of density difference between displacement fluid and displaced fluid, and the lower the displacement velocity, the better the cementing displacement efficiency. In addition, at the same condition of displacement parameter, cementing displacement efficiency at the section of small inclination is higher than that at the section of large inclination, and in the case of high density difference and low displacement velocity, the difference of displacement efficiency between different well deviation section is small, and the well inclination angle has a weak sensitivity to displacement efficiency. Under the different condition of well inclination angle, the influence sensitivity of density difference between displacement fluid and displaced fluid and displacement velocity to displacement efficiency is different. The fluid density difference and displacement velocity should be designed according to actual well conditions to obtain required cementing displacement efficiency. The research results provide a theoretical basis for optimizing cementing construction scheme indifferent sections of well inclination.

Keywords: Inclination Angle; Cementing Displacement; Physical Model; Mathematical Model; Displacement Efficiency

1. INTRODUCTION

The quality of cementing is decisive to the production life of oil and gas wells, and whether the cement slurry could displace the drilling fluid and annular space could be cemented completely or not, thus displacement efficiency largely determines the quality of cementing[1]. The cementing displacement efficiency is affected by well inclination, well diameter, center degree of casing, fluid density difference, rheological behavior, displacement velocity and other factors, so the displacement law is very complicated[2-3]. With the continuous expansion of oil and gas field development, more and more high deviated wells and horizontal wells with long section come into existence, while the influence of well inclination angle to the displacement efficiency can not be ignored[4-5]. The cementing displacement law is different at different well inclination angle, and the way to enhance displacement efficiency is different, thus it is necessary to study cementing displacement law of eccentric annulus at different well inclination angles[6-8].

Li Zhibin et al. [9-13] used CFD method to carry out numerical simulation study of displacement process and interior experiment study of displacement interface; Liu Yongfeng et al. [14] used software Fluent to simulate the displacement process of wellbore depression at different inclination angle; Feng Chun et al. [15-16] used software Fluent to simulate the influence of different well inclination angle on displacement efficiency under the condition of diameter expansion; Chen Ruifeng et al. [17]established a calculation model for the thickness of drilling fluid retention layer in the eccentric annulus of horizontal wells, and analyzed the influence of well inclination angle on cementing displacement efficiency in horizontal wells; Wang Binbin et al. [18]established a concentric annular displacement model and obtained displacement efficiency at different well inclination angles; Wang Lihong et al. [19-20] calculated and obtained the law of influence of casing buckling at different well inclination angles on cementing displacement efficiency through numerical simulation. In conclusion, many scholars have analyzed the influence of well inclination angle on displacement efficiency based on numerical simulation, that is, the larger the well inclination angle, the lower the displacement efficiency. Based on previous studies, under the condition of well inclination at 30°, 60° and 90°, considering center degree of 67%, coupling fluid density difference, and displacement velocity, the cementing displacement numerical simulation was carried by software CFD， and the effect law of density difference between displacement fluid and displaced fluid and displacement velocity under different well inclination and eccentric annular conditions are analyzed, and the optimization direction of displacement efficiency under different well inclination conditions are obtained, which provides a technical basis for improving cementing displacement efficiency in directional wells.

2. NUMERICAL MODEL

2.1 PHYSICAL MODEL

In order to study the cementing process under different well inclination angles, the 3D modeling software Gbmbit was used to draw the combination of casing-wellbore. According to the actual well condition, the annular cylinders with an inner diameter of 177.8mm, an outer diameter of 215.9mm, a length of 10m and 67% center degree were drawn, which could be rotated according to well inclination, and the inclination angels were set at 30°, 60° and 90° respectively. Since the cylinder has a symmetrical structure, the symmetric model is adopted, and half of the annulus is taken for numerical simulation.

In CFD numerical simulation, how to reasonably set a computing grid is the key to improve the accuracy. In this paper, displacement fluid volume fraction of the target section(displacement velocity × time) was selected as the test index and the independence of the grid was verified. The study found that when the number of the grid was more than 60,000, the test index changed little, and it basically satisfied the condition of the grid independence. Therefore, the number of 60,000 grids and the form of hexahedral structured grids were set to carry out numerical simulation calculation for the simulated well section. The casing-wellbore combination model in the inclination section is shown in Fig. 1

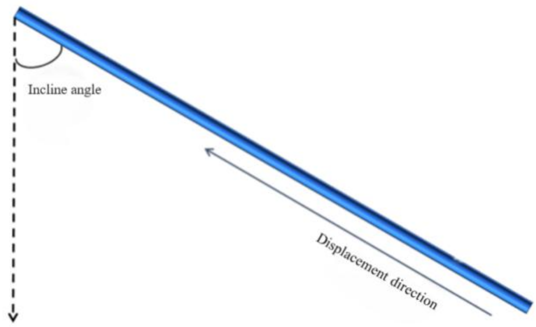


Fig.1 Schematic diagram of casing-wellbore combination model in inclination section

2.2 MATHEMATICAL MODEL

Numerical simulation of cementing displacement process was carried out based on the CFD software of computational fluid dynamics.The displacement interface can be observed well by using the VOF multiphase flow model to simulate the two phase of displacement fluid and displaced fluid. The phase volume fraction was introduced in the VOF model to track the displacement interface. The continuity equation and momentum equation contained therein are shown below.

$$\frac{\partial}{\partial t}(\alpha_1\rho_1)+\nabla\cdot(\alpha_1\rho_1 v_1)=S_{\alpha 1} \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_2\rho_2)+\nabla\cdot(\alpha_2\rho_2 v_2)=S_{\alpha 2} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla\cdot(\rho\vec{v}\vec{v})=-\nabla p+\nabla\cdot\left[\mu\left(\nabla\vec{v}+\nabla\vec{v}^T\right)\right]+\rho\vec{g}+\vec{F} \tag{3}$$

In which, α_1、α_2— phase volume fraction of the displacement fluid and displaced fluid, %; ρ_1、ρ_2—the density of displacement fluid and displaced fluid, $kg\cdot m^{-3}$; υ— the average displacement velocity at inlet boundary, $m\cdot s^{-1}$; $S_{\alpha 1}$、$S_{\alpha 2}$—mass fraction source item of the displacement solution and the displaced solution; F—surface tension of the displacement fluid and displaced fluid, $N\cdot m^{-1}$.

Where, $\alpha_1+\alpha_2=1$, the definition in the VOF model is as follows: if the grid is filled with displacement fluid, then $\alpha_1=1$; if the grid is filled with displaced fluid, then$\alpha_1=0$; if the displacement fluid and displaced fluid is mixed in a grid cell, then $\alpha_1=0\sim1$.

2.3 BASIC DATA OF NUMERICAL SIMULATION

In order to study the effect law of density difference and displacement velocity on displacement effect under different well inclination,numerical simulation of cementing displacement was carried out under different well inclination, different density difference and different displacement velocity, based on the actual data of a well in Wushi 17-2 Oilfield, in which non-Newtonian power-law fluid mode was used for the displacement fluid, while Bingham fluid mode was used for the displaced fluid. The basic parameters were shown in Table 1.

Table 1 Basic parameters of numerical simulation

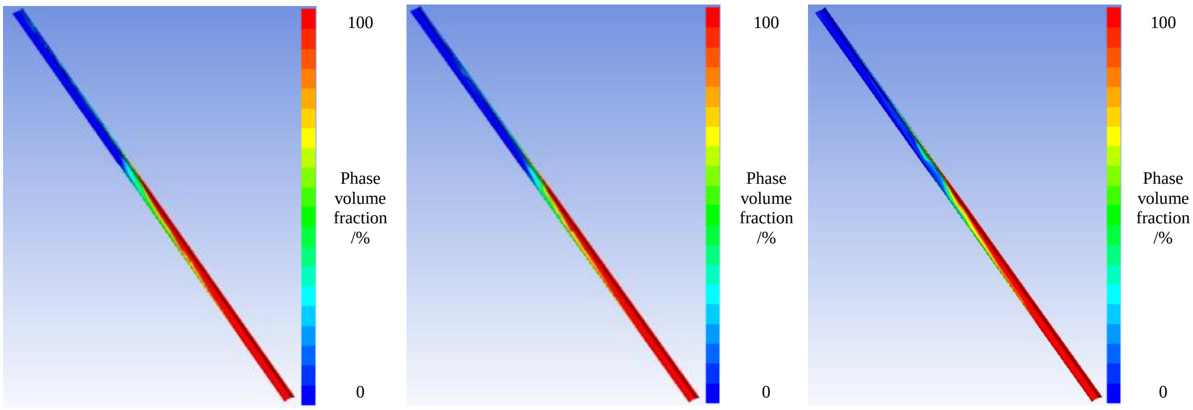
Physical parameter	Value
Casing center degree/%	67
Displacement fluid density /($g\cdot cm^{-3}$)	1.9
Displacement fluid consistency coefficient /($Pa\cdot S^n$)	0.7
Displacement fluid flow index	0.75
Displaced fluid density/($g\cdot cm^{-3}$)	1.3、1.5、1.7
Displaced liquid dynamic shear force /Pa	7
The plastic viscosity of displaced fluid/($mPa\cdot s$)	22
Displacement velocity/($m\cdot s^{-1}$)	0.3、0.6、0.9、1.2、1.5
Well inclination angle/°	30、60、90

3. NUMERICAL SIMULATION RESULTS AND ANALYSIS

In the simulation experiments of different well inclination sections, the influence of density difference and displacement velocity on cementing displacement efficiency were respectively discussed, then the numerical simulation results on different well inclination sections were compared to analyze the influence of well inclination angle on displacement efficiency, and the optimization direction of displacement efficiency in different well inclination sections was obtained.

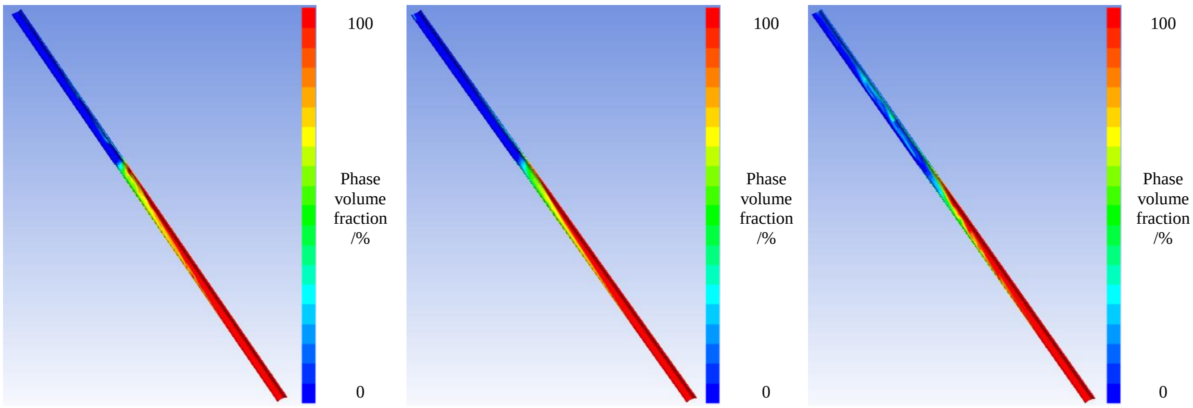
3.1 INFLUENCE OF FLUID DENSITY DIFFERENCE AND DISPLACEMENT VELOCITY ON CEMENTING DISPLACEMENT AT 30° WELL INCLINATION

Fig. 2-4 shows the phase volume fraction cloud map of the displacement fluid and the displaced fluid at a 30° well inclination angle,reflecting the interface morphological characteristics under different fluid density differences and different displacement velocities, in which red represents the displacement fluid, blue represents the displaced fluid, and the transition color is the mixed slurry section.According to the numerical simulation results, curves of cementing displacement efficiency and displacement interface length that changes with displacement velocity under different density differences are drawn, which is shown respectively in Fig. 5 and Fig. 6.



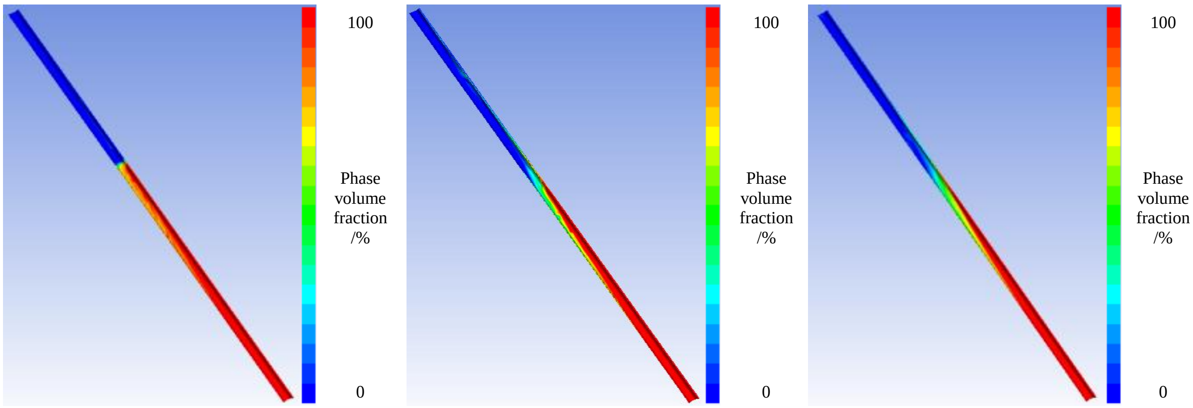
（a）Displacement velocity:0.3m/s （b）Displacement velocity:0.9m/s （c）Displacement velocity:1.5m/s

Fig.2 Phase volume fraction cloud map of cementing displacement at well inclination of 30°, density difference of 0.2g/cm^3 and different displacement velocities



（a）Displacement velocity:0.3m/s （b）Displacement velocity:0.9m/s （c）Displacement velocity:1.5m/s

Fig.3 Phase volume fraction cloud map of cementing displacement at well inclination of 30°, density difference of 0.4g/cm^3 and different displacement velocities



（a）Displacement velocity:0.3m/s （b）Displacement velocity:0.9m/s （c）Displacement velocity:1.5m/s

Fig.4 Phase volume fraction cloud map of cementing displacement at well inclination of 30°, density difference of 0.6g/cm^3 and different displacement velocities

It could be seen from Fig. 2-4 that with the increase of density difference between the displacement fluid and the displaced fluid, the displacement velocity decreases, the length of the displacement interface shortens, and the volume fraction of the displacement fluid gradually increases, which represents the gradual increase of cementing displacement efficiency. As can be seen from Fig. 5-6, the corresponding cementing displacement efficiency ranges from 90% to 97% and the length of cementing displacement interface ranges from 2 to 5m under the condition of well inclination angle of 30° and density difference of three fluids.With the increase of the fluid density difference, the displacement efficiency generally increases, mainly because the fluid buoyancy effect is enhanced with the increase of the density difference, and the high-density displacement fluid in the wide-gap annulus settles into the narrow-gap annulus, which inhibits the fingering phenomenon of the displacement fluid.In addition, with the decrease of displacement velocity, the length of cementing displacement interface is shortened and the displacement efficiency increases, mainly because the lower displacement velocity is helpful to restrain the displacement fluid fingering and facilitate the smooth advance of the displacement interface. It can be also found that when the density difference between the displacement liquid and the replaced liquid is small（0.2g/cm^3), the displacement velocity has little effect on the displacement efficiency and interface length; while when the density difference is large（0.4、0.6g/cm^3）, the displacement efficiency increases significantly with the decrease of the displacement velocity.For example, when the density difference between the displacement liquid and the replaced liquid is 0.6g/cm^3 and the displacement velocity is 0.3m/s, a relatively ideal displacement efficiency can be achieved, and the cementing displacement interface is basically flat, which is shown in Fig. 4 (a).

3.2 INFLUENCE OF FLUID DENSITY DIFFERENCE AND DISPLACEMENT VELOCITY ON CEMENTING DISPLACEMENT AT 60° WELL INCLINATION

Fig. 7 and Fig. 8 show the variation curves of cementing displacement efficiency and displacement interface length respectively that changes with displacement velocity under the condition of well inclination 60° and different density differences.The overall rule is similar to that under the condition of 30° well inclination, which the displacement efficiency shows a trend of increase with the increase of fluid density and the decrease of displacement velocity. However, the influence of density difference and interface length at a low displacement velocity is higher than that at a high displacement velocity. The reason is that the double factors of high fluid density difference and low displacement velocity inhibit the displacement fluid fingering better.

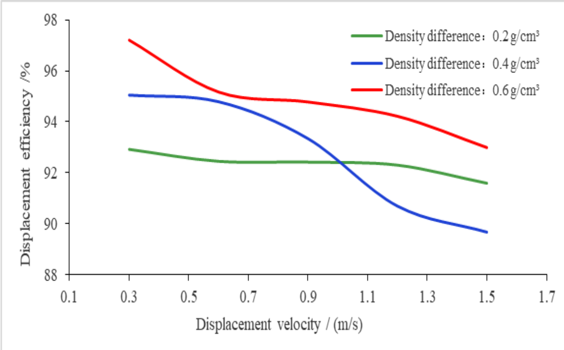


Fig.5 Influence curve of density difference and displacement velocity on the displacement efficiency under the condition of well inclination of 30°

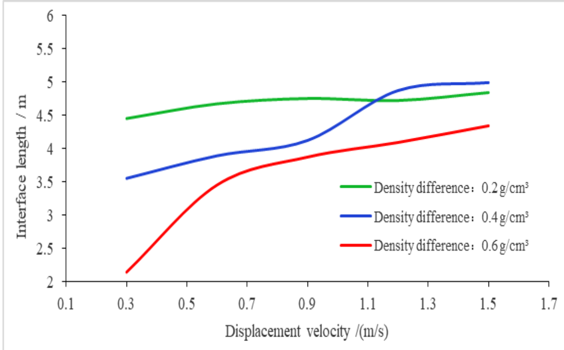


Fig.6 Influence curve of density difference and displacement velocity on the displacement interface length under the condition of well inclination of 30°

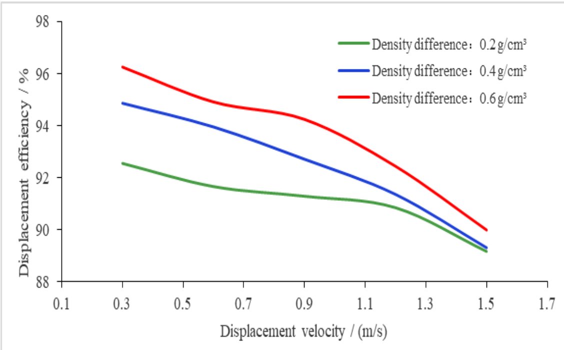


Fig.7 Influence curve of density difference and displacement velocity on the displacement efficiency under the condition of 60° well inclination angle

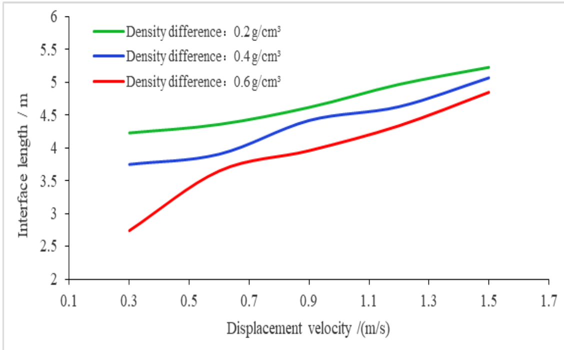


Fig.8 Influence curve of density difference and displacement velocity on the displacement interface length under the condition of 60° well inclination angle

3.3 INFLUENCE OF FLUID DENSITY DIFFERENCE AND DISPLACEMENT VELOCITY ON CEMENTING DISPLACEMENT AT 90° WELL INCLINATION

Fig. 9 and Fig. 10 show the variation curves of cementing displacement efficiency and displacement interface length respectively that changes with displacement velocity under the condition of well inclination 90° and different density differences. The general rule is similar to that under the condition of 60° well inclination angle. With the increase of fluid density difference, the displacement velocity decrease, and the displacement efficiency shows an increasing trend. However, the influence of displacement velocity on displacement efficiency and interface length in the condition of high density difference（0.6g/cm^3）is higher than that in the condition of low（0.2g/cm^3）or medium（0.4g/cm^3）density difference. The reason is that under the condition of horizontal wellbore, the buoyancy effect of high-density displacement fluid on the low-density displaced fluid along the displacement direction is lost, the effect of inhibiting displacement fluid fingering caused by density difference is weakened, which makes displacement velocity that inhibits displacement fluid fingering become a dominant factor, while the displacement velocity under the condition of high density difference is more sensitive to inhibit displacement fluid fingering.

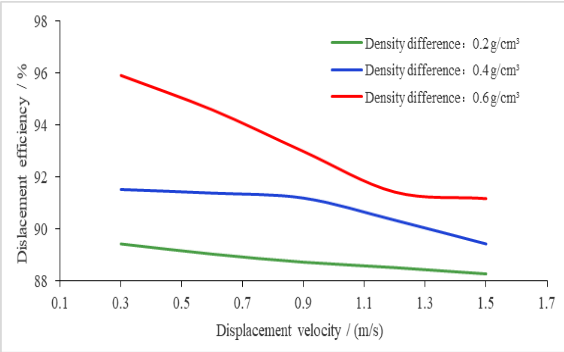


Fig.9 Influence curve of density difference and displacement velocity on the displacement efficiency under the condition of 90° well inclination angle

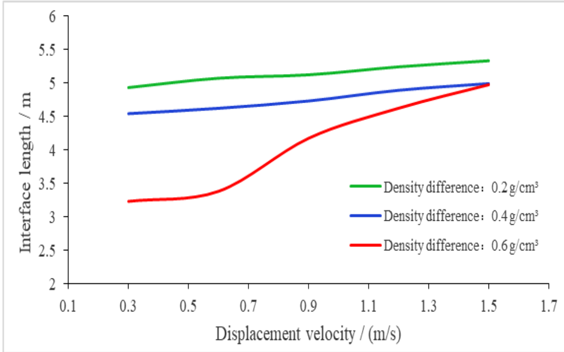
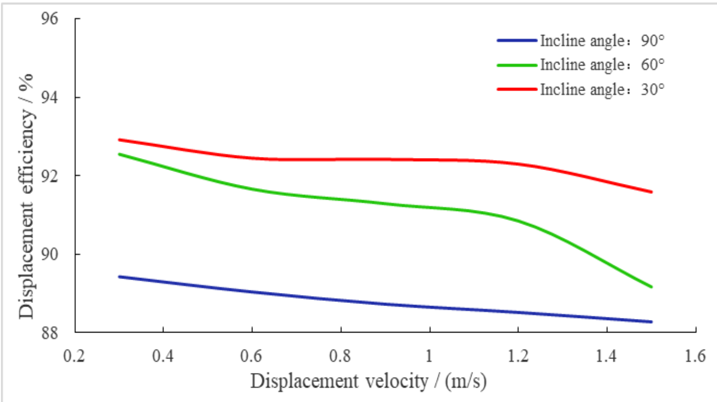


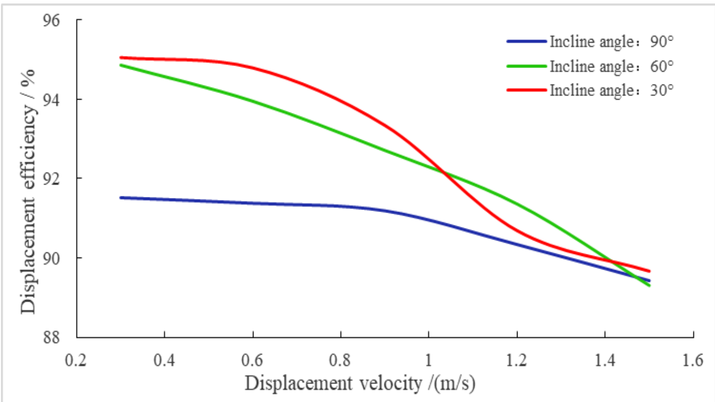
Fig.10 Influence curve of density difference and displacement velocity on the displacement interface length under the condition of 90° well inclination angle

3.4 ANALYSIS OF EFFECT LAW OF WELL INCLINATION ANGLE ON CEMENTING DISPLACEMENT EFFICIENCY

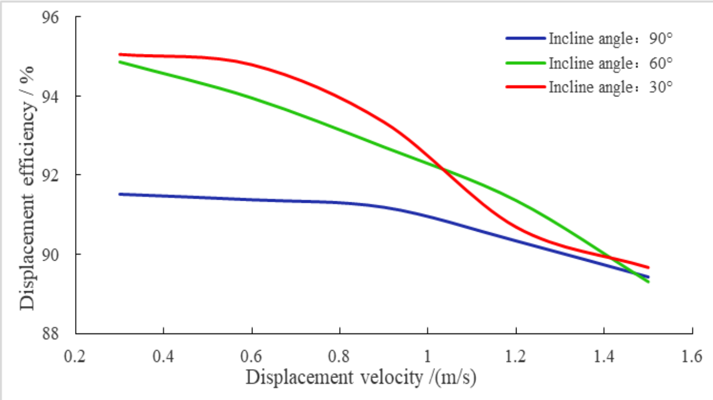
In order to obtain the effect law of well inclination angle on cementing displacement efficiency, under the condition of 30°, 60°, 90° well inclination angle, the calculation results of displacement efficiency were statistically analyzed, and the variation curves of cementing displacement efficiency that changes with the displacement velocity under the condition of different density difference were obtained, which is shown in Fig.11.



(a) Density difference of $0.2g/cm^3$



(b) Density difference of $0.4g/cm^3$



(c) Density difference of 0.6g/cm^3

Fig.11 Influence curve of well inclination angel on displacement efficiency under different density difference

It can be seen from Fig.11 that under the condition of same displacement parameters, the cementing displacement efficiency of the small inclination section is higher than that of the large inclination section. The reason is that with the decrease of well inclination, the gravity component of drilling fluid in the opposite direction of displacement increases, which suppresses the displacement fluid flow. In the meantime,the fingering phenomenon of the displacement fluid in the wide gap annulus is inhibited, which makes the displacement interface more stable, and it leads to the improvement of the displacement efficiency. In addition, under the condition of high-density difference（0.6g/cm^3）, the influence of well inclination angle on displacement efficiency is less sensitive, especially in the case of low displacement velocity, and the difference of displacement efficiency between different well deviation sections is small.This is mainly because the dual factors of high fluid density difference and low displacement velocity. They have a good inhibiting effect of displacement fluid fingering, while the weight of well inclination is relatively small.

4. CONCLUSION

(1) Under the same condition of well inclination, with the increase of density difference between displacement fluid and displaced fluid, the cementing displacement efficiency generally increases, and the lower displacement velocity, the greater cementing displacement efficiency. It is mainly because the buoyancy effect caused by high fluid density difference and low displacement velocity, which have a good inhibiting effect on displacement fluid fingering.

(2)Under the same displacement parameters, the cementing displacement efficiency in the small well inclination section is higher than that in the larger well inclination section.In the case of high density difference and low displacement velocity, the difference of displacement efficiency in different well inclination sections is small, and the well inclination angle has a weak sensitivity to the influence of displacement efficiency.

(3) Under the condition of different well inclination angels, the density difference between displacement fluid and displaced fluid and displacement velocity have different sensitivity on the influence of displacement efficiency. the fluid density difference and displacement velocity could be designed by actual well conditions to acquire the required cementing effect.

5. ACKNOWLEDGEMENTS

This work was supported by grants from the key project of CNOOC (China) Co., Ltd. "Research on the key technologies of drilling and completion of 20 million m^3 oil field in the west of south China sea"（CNOOC-KJ135ZDXM38ZJ05ZJ), National Natural Science Foundation of China (Project No. 51804043), the Yangtze fund for youth teams of science and technology innovation (2016cqt03). Here, I would like to express my deep gratitude.

REFERENCES

[1] Li Wenjuan, Tang Shizhong. Countermeasure Study on Improving Cementing Quality of Large Inclination Wells in Chenghai block one[J]. *Petroleum Geology and Engineering*,2014,28(02):126-128+150.

[2] Wei Kai,YanZhenfeng,XiongQingshan,GuoZhiyang,FuJiawen,LuanJiacui. Phase-field simulation of slurry displacement efficiency in borehole with a sudden contraction or expansion[J]. *Journal of Petroleum Science and Engineering*,2021,196.

[3] Hanieh K. Foroushan, Evren M. Ozbayoglu, Paulo J. Gomes. How Realistic is the Calculated Cementing Displacement Efficiency [C]. *IADC/SPE International Drilling Conference and Exhibition*, March 3–5, 2020.

[4] Mostafa Sedaghatzadeh,KhalilShahbazi,Mohammad Hossein Ghazanfari,GhasemZargar. The Impact of Nanoparticles Geometry and Particle Size on Formation Damage Induced by Drilling Nano-Fluid during Dynamic Filtration[J]. *Journal of Nano Research*,2016,4477.

[5] Hai Jing Wang,Shi Feng Xue,Xing Hua Tong. Inflow Performance for Slanted Wells in Anisotropic Reservoirs Considering Wellbore Pressure Drop[J]. *Advanced Materials Research*,2012,1792.

[6] Zheng Zhongmao, Liu Tianen, Zhou Baoyi, Zhang Tie. Effect of Buoyance on Casing Central Degree of High Angle Deviated Well[J]. *Oil Drilling&Production Technology*,2017,39(03):313-318.

[7] HoubinLiu,ShuaiCui,YingfengMeng,XiangyangZhao,Xu Han. Influence of relation between stress field and bedding space on wellbore stability in shale formation[J]. *Arabian Journal of Geosciences*,2019,12(20).

[8] Kai Zhao,JunliangYuan,YongcunFeng,Chuanliang Yan. A novel evaluation on fracture pressure in depleted shale gas reservoir[J]. *Energy Science & Engineering*,2018,6(3).

[9] LiZhibin. The research on improving displacement efficiency of highly deviated wells with eccentric annulus[D]. *China University Of Petroleum* (East China),2014.

[10] Bu Yuhuan, GuoShenglai, Li Zhibin. Indoor Experimental Device for Simulate Cementing Displacement of Highly Deviated Wells[J]. *Research and Exploration in Laboratory*,2014,33(10):55-60+221.

[11] WenxiuDong,XiaodongWang,Jiahang Wang. A new skin factor model for partially penetrated directionally-drilled wells in anisotropic reservoirs[J]. *Journal of Petroleum Science and Engineering*,2018,161.

[12] Alondra Renteria,AmirMaleki,IanFrigaard, BjornarLund,AliTaghipour,Jan David YtrehusDisplacement. Efficiency for Primary Cementing of Washout Sections in Highly Deviated Wells[C]. *SPE Asia Pacific Oil and Gas Conference and Exhibition*, October 23–25, 2018.

[13] Li Mingzhong, Wang Chengwen, Wang Changquan, GuoShenglai, Fang Qun. Numerical Simulation of Cement Displacement in Eccentric Annulus at Highly Deviated Wells[J]. *Petroleum Drilling Techniques*, 2012,40(05):40-44.

[14] Liu Yongfeng. The numerical study of the process for the wellbore sag area cementing displacement flowing and displacement efficiency[D]. Xi'an Shiyou University,2017.

[15] Feng Chun. Well cementing replacement flow regime selecting and computing method of coal bed gas[D]. *Northeast Petroleum University*,2012.

[16] Zhang Ligang, JinXianpeng, LvDeqing. Displacement efficiency of cementing in CBM well[J]. *Coal Geology& Exploration*,2014,42(03):43-46.

[17] Chen Ruifeng. Research on flow process calculation of cementing in horizontal well[D]. Southwest Petroleum University[D]. *Southwest Petroleum University*,2017.

[18] Wang Binbin, Wang Ruihe, Bu Yuhuan. Numerical simulation of annular displacement of cement slurry with different flow regimes[J]. *Drilling fluid＆Completion fluid*,2010,27(03):76-78+83+100-101.

[19] Wang Lihong, Wang Jintang, Tong Zeliang, Zhou Guobin. Influence analysis of casing buckling in extended reach well[J]. *Journal of Qufu Normal University*,2015,41(02):42-49.

[20] Wang Jintang, Sun Baojiang, Li Hao, Cao Chengzhang, Peng Zhigang, Xu Kewang. Simulation analysis of rotating-casing cementing displacement in extended reach well[J]. *Journal of China University of Petroleum*, 2015,39(03):89-97.