Present Situation Research on Axial Flow Displacement Theory During Cementing

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Abstract

It is well known that displacing drilling fluid effectively is the premise to obtain good cementing quality. During cementing axial flow is the major way to displace annular drilling fluid. So we put emphasis on the research of axial flow displacement theory. At present axial flow displacement theory mainly focuses on three aspects: displacement theory study based on wall shear stress; displacement theory study based on the numerical simulation technique for the displacement interface stability; displacement theory study based on laboratory experiments. In this paper, we analyzes the present research situation and their respective advantages and defects of the above mentioned three aspects in displacement theory. We put forward that infinitesimal mechanical analysis for displacement interface and numerical simulation technology for the interface stability should combine organically. In order to achieve good cementing effect, we should stress on the research and measurement of profile displacement efficiency and put the interface moving steadily as a prerequisite. As a result, our research can lay a fundamental the future development of axial flow displacement theory.

INTRODUCTION

Displacing drilling fluids effectively and increasing cementing displacement efficiency are the basic premises to prevent drilling fluid from channeling and ensure slurry cement quality and sealing effect. Thus axial flow displacement theory in cementing process is always the studying focus for the cementing community at home and abroad. Recently the study of axial flow displacement theory mainly focuses on three aspects: (1) Establishing the mechanical displacement model by mechanical analysis which is based on wall shear stress theory of displacing fluid. Besides, proposing the condition of drilling fluid retention. (2) simulating the stability of displacement interface using fluid dynamics software and analyzing displacing process and effect from fingering instability of displacement interface. (3) analyzing the effect of single factor on the displacement efficiency via laboratory displacing experiments and finally achieving the requirement of displacing fluid properties. This paper analyzes the status of the above the mentioned three displacement theory and their advantages and disadvantages, which provides some research ideas for the development of axial flow theory and technology.

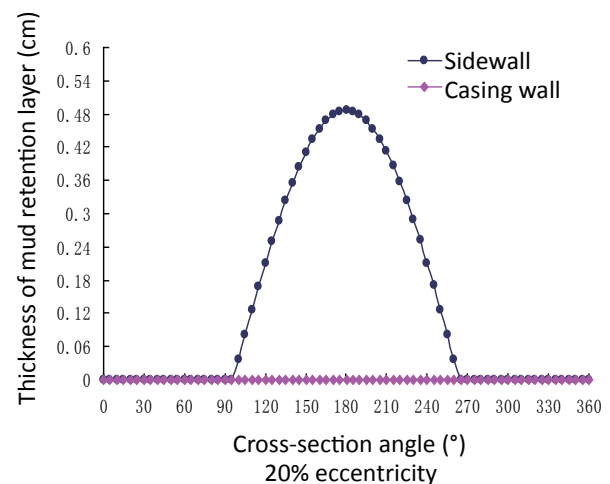# 1. DISPLACEMENT THEORY STUDY BASED ON WALL SHEAR STRESS

The shear force that acts on annular walls can be created when slurry flows along the annulus. Shear force in unit area of the annulus is called wall shear stress[1-3]. Wall shear stress is a major power to clean the drilling fluid that is attached to the sidewalls. Therefore, it plays a decisive role on improving slurry displacement efficiency. Wall shear stress is composed of the flooding pressure, the viscous force of flowing slurry acting on drilling fluid and the buoyancy caused by density difference. we can use it to reflect the effect of operating parameters and fluid's properties on displacement efficiency.

The wall shear stress of turbulent flow is generally greater than the one in other flow states, the same value of which can be obtained by increasing fluid's plastic viscosity and yield stress. In the development process of cementing technology, a variety of displacement technologies, such as plug flow displacement technology, turbulent flow displacement technology and effective laminar flow displacement technology. There is no doubt that each of them can find many successful examples. The design idea of wall shear stress is also very consistent with the achievements of these technologies.

1.1 Displacement Theory for Vertical Well Based on Wall Shear Stress

Mclean R. H.[4] defined the concept of critical yield stress in 1967. He thought slurry displacement efficiency could be improved obviously when the yield stress of slurry was 0.8-1.5 times the critical yield stress. Buoyancy was produced by the density difference between slurry and drilling fluid contributed to raising displacing effect. Parker[5-6] indicated that residual drilling fluid in the wellbore expanding place would decrease if the technology of plug flow displacement whose uphole velocity is lower than 0.5 m/s was used in cementing. Hault and R. J. Crook[7-9] concluded that mud cake performance and the maximum gel strength were the two major factors that affected slurry displacement efficiency based on experiments. Immobile mud cake and drilling fluid being detained in the wellbore because of its thixotropy couldn't be displaced fully. So better displacing effect could be obtained by using higher uphole velocity than lower. Based on the flow characteristics of slurry and drilling fluid in slim hole and small clearance, Liu Chongjian[10] proposed that cementing displacement efficiency in small clearance could be improved through adjusting the ratio of pressure gradient and yield stress between slurry and drilling fluid. with the method of combining theory with experiment in 2003. Besides some parameters such as casing eccentricity, contact time of turbulent flow and thixotropy of drilling fluid that were helpful to improving cementing displacement efficiency

in small clearance were specified. Li Zaoyuan[11] created cementing techniques of ground adjusting drilling fluid properties before cementing and displacing mud by turbulent pad fluid at low return velocity in 2005. Stable flow profile could be achieved through lowering the yield stress, plastic viscosity and gel strength of drilling fluid and using the technique of turbulent pre-flushing at low return velocity. Song Huiguang[12] analyzed the effect of rheological parameters on slurry flow velocity in 2009. He thought the residual drilling could be transformed more easily by adjusting the distribution of slurry velocity which depended on the rheological parameters. As a result, cementing displacement efficiency was improved with this method. Feng Fuping[13] analyzed the shear stress of drilling fluid under the condition of laminar displacement of Bingham fluid. Besides, based on equilibrium conditions for the stabilization of the displacement interface, a model to calculate boundaries and thickness of mud retention layers at sidewalls and casing depths with different circumferential angles in eccentric annulus was established in his context. The calculation showed that with the increase of casing eccentricity, the displacement efficiency at the wide gap changed little, while that at the narrow gap was falling sharply and mud channeling was more readily to form. Mud retention layers occurred first at sidewalls where the thickness and extent of retention layers were much greater than those at casing depths (Figure 1). Deng Jianmin[14] studied that a vertical well fluid displacing was analyzed assuming power-law fluid with laminar flow during the cementing displacement process in 2011. On the basis of this analysis, a method and formula was established to calculate the fluid density and rheological parameters by which the displacing and displaced fluids had the same velocity in flow of replacement. In addition, A set of fluid performance parameters that contributed to improving cementing displacement efficiency were given in the paper.
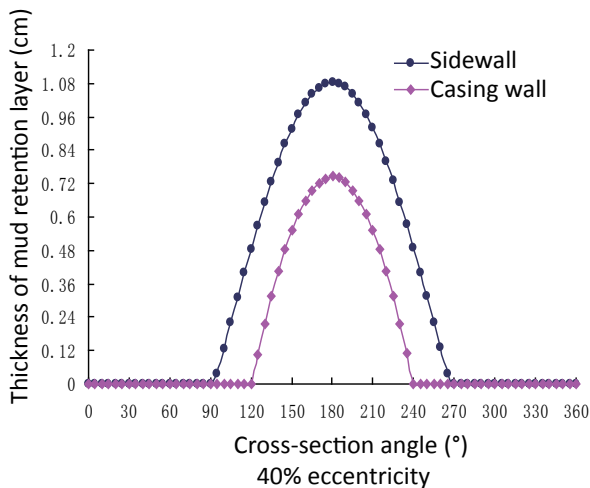
Figure 1
Thickness Distribution of Mud Retention Layer in Different Eccentricity

1.2 Displacement Theory for Horizontal Well Based on Wall Shear Stress

Heavy slurry tends to flowing toward the bottom hole owing to the density difference between slurry and drilling fluid in horizontal wells, which leads to creating spiny and fingerlike velocity profile. As a result, the light drilling fluid that gathers in the up hole is hard to displace and builds continuous channel at sidewalls finally. Zheng Yonggang[15] systematically studied the displacing mechanism in cementing based on the displacement model of flat plate laminar flow and laboratory experiment in 1996. He concluded that the density difference between slurry and drilling fluid didn't benefit to improving displacement efficiency. Therefore, small or zero density difference would achieve better results in cementing process. Feng Fuping[16] proposed driving force that generated by the density difference between slurry and drilling fluid was the function of circumferential angle and borehole radius. The driving force became larger in the bottom hole, which made the displacement interface extend more easily. When the density difference was positive, drilling fluid at sidewalls and casing walls of upper annulus remained most. The thickness of mud retention layers became smaller as the position was close to bottom hole and was thinnest in the bottom hole finally. However, opposite results would achieve when the density difference was negative. Figure 2 showed the final displacing result. The law provided a reasonable theoretical basis for the cementing technique[17] design of dual density circulation fluid and double density slurry in horizontal wells in Mobil Oil. The cementing process was: firstly, low density slurry that was lower than the drilling fluid's in horizontal sections was used in cementing, as a result, which made the drilling fluid in up hole clean. Then higher density slurry was pumped, which made the drilling fluid in bottom hole displaced under the role of positive density difference. Finally, the entire horizontal

section had no residual drilling fluid and achieved good displacement effect. Meanwhile the effect of casing eccentricity on displacing effect in horizontal wells was analyzed. The displacement efficiency decreased and the thickness discontinuity of annular cement sheath increased as the increase of eccentricity when casing was upper eccentricity, while the displacement efficiency increased and the thickness of annular cement sheath tended to be uniform at first and to be uneven as increase of eccentricity when casing was lower eccentric. The casing lower eccentricity of 0.1 to 0.2 in horizontal well could bring about the best cementing quality, so the casing upper eccentric should be strictly controlled to prevent whole drilling fluid retention and uneven distribution of cement sheath thickness.
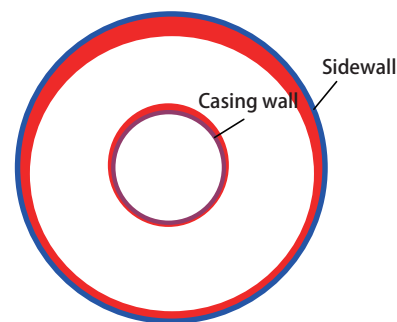

Figure 2
Displacement Effect of Annular Drilling Fluid in Horizontal Wells (The red colour represents the resident drilling fluid)

1.3 Advantages and Disadvantages of Displacement Theory Based on Wall Shear Stress

The displacement theory based on wall shear stress applies the method of microelement mechanics analysis into the process of slurry displacing drilling fluid. The advantages of the theory are:

(1) By mechanics analysis on the infinitesimal body of drilling fluid, how the annular drilling fluid remains can be reasonably explained, which provids a theoretical basis for adjusting slurry performance and operating parameters;

(2) The profile displacement efficiency will be an analysis object in displacement theory based on wall shear stress. The position and thickness of resident drilling fluid in local section can be achieved, which provids a theoretical basis for how clean the drilling fluid in local section.

However, the disadvantages of the theory are:

(1) The mixing and separating phenomenon of displacing and displaced fluid in the interface cannot be described;

(2) The fingering phenomenon of laminar flow cannot be described in cementing, besides the dynamic process of displacement interface cannot be simulated.

2. DISPLACEMENT THEORY STUDY BASED ON NUMERICAL SIMULATIONS OF DISPLACEMENT INTERFACE

On the basis of Arbitrary Lagrangian and Eulerian finite element method, Szabo P.[18] used high-viscosity Newtonian fluid that was characterized non-Newtonian fluid to simulate the buoyancy effect on displacement efficiency in a vertical annulus in 1997. Using volume of fluid method and laminar flow model in FLUENT software, Eduardo S.[19] studied the velocity difference in the wide and narrow space of eccentric annulus and the effect of casing eccentricity on fluid fingering phenomenon in 2004. Dutra E.S.S.[20] used FLUENT software to study the mechanism of chemical cleaning fluid and slurry displacing annular pad fluid and drilling fluid in 2005. Besides, he analyzed the effect of differences in fluid density and rheological parameters on displacement. Gao Yonghai[21-22] used k-ε turbulence model in FLUENT software to simulate the relationship between casing eccentricity and injection rate and displacing interface stability in a vertical annulus. He proposed that the stability of displacing interface can be improved by lowing the flow index, consistency coefficient and yield stress of pad fluid. Yang Jianbo[23] used numerical simulation technique to study the process of annular displacement in 2008. He thought that: the casing eccentricity and non-positive density difference would affect the displacement interface stability; when displacement happened at a low velocity, positive density can obtain the best effect, while the negative density worst; using larger positive density can decrease the effect of casing eccentricity on displacement efficiency in the process of low-velocity displacement in eccentric annulus (as is shown in Figure 3).
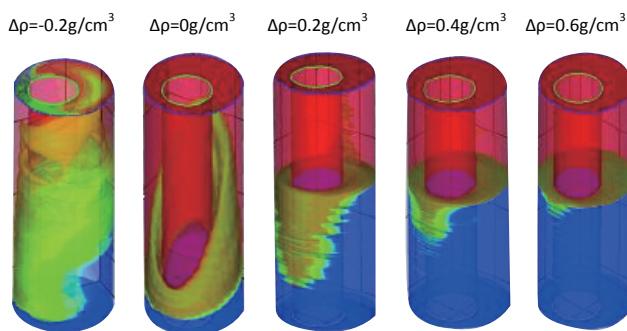
$\Delta\rho=-0.2g/cm^3$ $\Delta\rho=0g/cm^3$ $\Delta\rho=0.2g/cm^3$ $\Delta\rho=0.4g/cm^3$ $\Delta\rho=0.6g/cm^3$

Figure 3
Displacement Interface of Different Density Difference Under Casing Eccentricity 0.5

The advantages of numerical simulation technique based on the displacing interface stability are as follows:

(1) the software can display intuitively the mixing phenomenon of two fluids displacement interface with time;

(2) the software can simulate the instable phenomena of displacement interface, such as disengagement and fingering, in different annular space with time.

However, the disadvantages of numerical simulation technique based on the displacing interface stability are as follows:

(1) because only the velocity at sidewalls is custom zero in FLUENT software, fluid at any point in the annulus was flowing. So if only the displacing time was enough, resident drilling fluid would not exist in the annulus. That is to say, the displacement efficiency is 100%;

(2) the software cannot describe the mechanism of drilling fluid retention and can only describe the displacement effect of interface. In addition, the overall displacing results had a big difference with actual value.

3. DISPLACEMENT THEORY STUDY BASED ON LABORATORY EXPERIMENTS

GC. Howard and J. B. Clark[24] recognized the importance of drilling fluid properties by a cementing displacement simulation experiment in 1948. Increasing slurry's return velocity and reducing the viscosity had an important role to improve the displacement efficiency. Brice[25] proposed that displacement efficiency can be effectively improved if the time that turbulent slurry contacted with sealing layer was less than 10 minutes. The country began to study the mechanism of cementing displacement since 1984. Southwest Petroleum Institute and the drilling institute of Daqing Petroleum Administration Bureau created dynamic experiment devices of simulating annular displacement. a large experimental study showed that: casing eccentricity, the flow pattern of slurry, turbulence contact time, the drilling fluid thixotropy and the density difference between slurry and drilling fluid were important factors that can affect slurry displacement efficiency. Among them, the casing eccentricity, turbulent flow pattern and turbulence contact time were the most important factors. Jakobsen[26] created experiment devices of dynamic cementing by fluorescent traccer technique in 1991. According to this technique, Southwest Petroleum Institute created similar experimental devices and more factors were studied theoretically and experimentally. Zhang Xingguo[27-28] studied the effect of turbulence contact time and drilling fluid thixotropy on cementing displacement efficiency in 2005. The results showed that: increasing the degree of turbulence and prolonging turbulence contact time would help improve the displacement efficiency, but the efficiency wouldn't continue increase with turbulence contact time prolonging. So it was not necessary for obtaining a longer contact time to increase the pumping amount of flushing fluid, separating fluid and slurry too much. Because the drilling fluid was more difficult

to displace with its thixotropy increasing, reducing the drilling fluid thixotropy properly before cementing can improve the displacement efficiency. Yang Jianbo[29] developed experimental devices of simulating cementing process in eccentric annulus in 2007. He studied the effect of density difference on the displacement interface by displacing test of bentonite similitude liquid. The results showed that: When density difference between the displacing fluid and displaced fluid was positive, the slug flow displacement effect was better than that of low-velocity laminar flow. When density difference was negative, the displacement efficiency improved with the increase of Reynolds number. During the eccentric annulus displacement at a low rate, using large positive density difference can overcome the decentralization impact and improve the displacement efficiency.

The advantages of displacement theory based on laboratory experiment are:

(1) As the borehole conditions are complex, there are large errors for the actual evaluation results of displacement efficiency. However, a more accurate displacement efficiency can be achieved in laboratory experiments, which provids reference for the study of displacement theory.

(2) Many factors can affect the displacement efficiency, and there is a big difference in each well. Because experimental conditions can be controlled, the effect of single factor on displacement efficiency can be achieved under the condition of other factors unchanged.

The disadvantages of displacement theory based on laboratory experiment are:

(1) Because the cementing conditions in laboratory and well site are different, the laboratory experiment cannot truly reflect the actual displacement conditions of downhole.

(2) The laboratory experiment can only measure overall displacement efficiency, and it cannot explain the relationship between profile displacement efficiency and various factors.

4. DEVELOPMENT DIRECTION OF AXIAL FLOW DISPLACEMENT THEORY IN CEMENTING

(1) Analysis of displacement efficiency on the local profile should be emphasized in the displacing mechanism. Microelement mechanics and stability of the displacing interface should be also analyzed accurately. Besides, we should combine the displacing mechanical mechanism with numerical simulation techniques effectively.

(2) Fully considering the actual conditions of downhole, these devices that can estimate the dynamic expansion of displacement interface in real time and displacement effect on the profile should be created.

(3) The theory of effective laminar flow displacement

should be emphasized. In condition of meeting the effective wall shear stress, axial flow displacement effect can be improved through achieving displacement interface uniform advancing, forming a stable displacement interface and improving profile and overall displacement efficiency in the cementing process.

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