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The Multiphase Flow System Used in Exploiting Depleted Reservoirs: Water-based Micro-bubble Drilling Fluid

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Abstract. Water-based micro-bubble drilling fluid, which is used to exploit depleted reservoirs, is a complicated multiphase flow system that is composed of gas, water, oil, polymer, surfactants and solids. The gas phase is separate from bulk water by two layers and three membranes. They are “surface tension reducing membrane”, “high viscosity layer”, “high viscosity fixing membrane”, “compatibility enhancing membrane” and “concentration transition layer of liner high polymer (LHP) & surfactants” from every gas phase centre to the bulk water. “Surface tension reducing membrane”, “high viscosity layer” and “high viscosity fixing membrane” bond closely to pack air forming “air-bag”, “compatibility enhancing membrane” and “concentration transition layer of LHP & surfactants” absorb outside “air-bag” to form “incompact zone”. From another point of view, “air-bag” and “incompact zone” compose micro-bubble. Dynamic changes of “incompact zone” enable micro-bubble to exist lonely or aggregate together, and lead the whole fluid, which can wet both hydrophilic and hydrophobic surface, to possess very high viscosity at an extremely low shear rate but to possess good fluidity at a higher shear rate. When the water-based micro-bubble drilling fluid encounters leakage zones, it will automatically regulate the sizes and shapes of the bubbles according to the slot width of fracture, the height of cavern as well as the aperture of openings, or seal them by making use of high viscosity of the system at a very low shear rate. Measurements of the rheological parameters indicate that water-based micro-bubble drilling fluid has very high plastic viscosity, yield point, initial gel, final gel and high ratio of yield point and plastic viscosity. All of these properties make the multiphase flow system meet the requirements of petroleum drilling industry. Research on interface between gas and bulk water of this multiphase flow system can provide us with information of synthesizing effective agents to enlarge the application of micro-bubble in petroleum industry.

1. INTRODUCTION

Mr Sebba (1987) found a kind of special biliquid foams called Aphron. It was Brookey (1998) who first introduced aphron into petroleum drilling industry and renamed aphrons as “micro-bubbles”. Up to now, water-based micro-bubble drilling fluid (WMDF) has been drilled thousands of depleted reservoirs without any lost circulation problem. Laboratory experiments indicate that WMDF has very little spurt loss (Tom Brookey, 1998), has very high yield stress at extreme low shear rate, and can accumulate energy (C.D. Ivan et al., 2002). Many researchers think that micro-bubbles have the same structure as aphron (F.B. Growcock et al., 2003). But the recent research on the structure of "micro-bubble" indicates that it is slightly different from the structure of aphron because gas, water, oil, polymer, surfactants and solids exist in WMDF at the same time which would affect the structure. And it is the real structure of micro-bubble that explains mechanism for lost circulation controlled by WMDF and enables the drilling fluid system with good rheological properties to meet the requirements of petroleum drilling industry.

2. STRUCTURE

According to Sebba (1987), aphron is a soppy shell absorbing some surfactants staying in bulk water, as fig.1 shows. Different from aphron, except surfactants there are still some linear high polymers (LHP) and solids in bulk water, so micro-bubble in WMDF should have the structure as fig.2 shows.

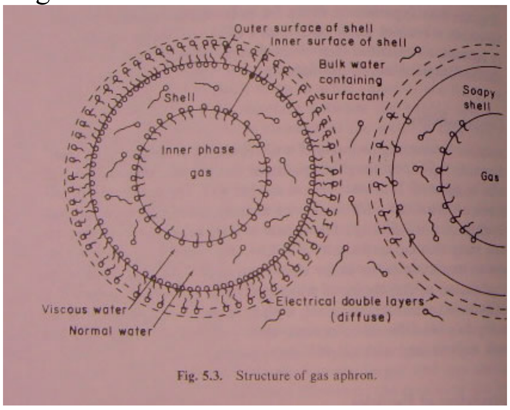

Fig. 1 Structure of aphron

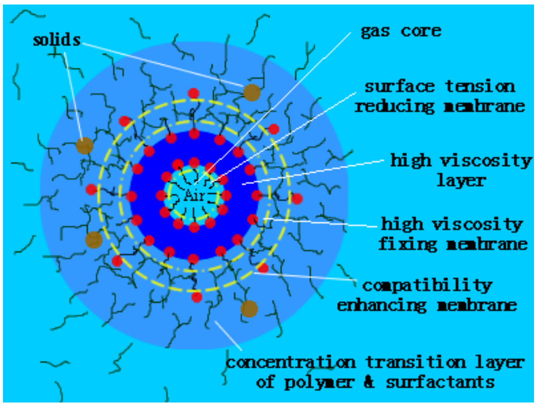

Fig. 2 Structure of micro-bubble

Fig.2 reveals a picture on which gas is wrapped by an aqueous coat that holds surfactants on both sides. The inner side surfactants point their hydrophobic ends to the gas core while hydrophilic ends residing within the aqueous coat. By contrast, the outer side surfactants have their hydrophilic ends reside within the aqueous coat while the hydrophobic ends stretching to the bulk water. LHP and surfactants in bulk water adhere outside the outer surfactants closely through van der Waals force forming a layer which has much higher concentration. With the attractive force reducing, concentration of LHP and surfactants decreases gradually. Little by little, concentration goes back to the same level as it is in bulk water after a few distances from the outer surfactants. In addition, some solids mixed with LHP appear in the higher concentration layer.

The gas, which is wrapped by aqueous coat and lying in the center of the micro-bubble, looks like a core. We name the core "gas core" and call the aqueous coat "high viscosity layer", for it is a special phase which has much higher viscosity than bulk water. The inner side surfactants, which is used to reduce the surface tension between gas and water, is named as "surface tension reducing membrane", while the outer side surfactants, which is used to keep the high viscosity of aqueous coat, is called "high viscosity fixing membrane". The closely adsorbed LHP and surfactants form a layer which is called "compatibility enhancing membrane", for they can enhance the compatibility of micro-bubble and bulk water, while the loosely adsorbed LHP and surfactants, which have changeable concentration and indefinite radium, are dimmed as "concentration transition layer of LHP & surfactants". "Gas core", "surface tension reducing membrane", "high viscosity layer" and "high viscosity fixing membrane" often work as a unit for "surface tension reducing membrane", "high viscosity layer" and "high viscosity fixing membrane" connect with each other through hydrogen bond, which is a relatively strong bond and will not be destroyed easily. We name the unit "air bag". However, it is the LHP and surfactants that form "compatibility enhancing membrane" and "concentration transition layer of polymer & surfactants". They connect with each other through van der Waals force and sensitization, which are relatively weak bond forces. So, the radium of the two parts can be changed easily and even these two parts can be destroyed by the outside force like diffusive force which makes the boundary between two parts indistinct. For the sake of decscribing easily, we merge the latter two parts as another unit and name it “incompact zone”.

3 CHARACTERS

Aphron is a double layer micro-bubble which is weakly bonded by a layer of surfactants while the micro-bubble in WMDF is an “air-bag” wrapped by an “incompact zone”. On the one hand, “incompact zone” wraps the “air-bag” and makes it water wetted, and keeps the whole system stable for a period of time. On the other hand, LHP and surfactants in “incompact zone” can diffuse into the bulk water while the opposite process is also realizable. Hence, “incompact zone” can separate from “air-bag” easily by the outside force and that will diminish air-bag’s water wettability but enhance its hydrophobic ability. The dynamic changes of “incompact zone” lead the WMDF system to have its macro characteristics changing. These changesable characters will meet the requirements of petroleum drilling.

3.1 Micro-bubble’s Existence and Its Wetting Behavior

Observing the micro-bubbles in WMDF through microscope, Growcock (2003) found that micro-bubbles can separate into bulk water automatically. He also discovered that several micro-bubbles may assemble together but perform as an individual micro-bubble. Experiments also show that micro-bubbles can form a bubble band if there is a pressure difference (F.B. Growcock, A. Belkin, M. Fosdick et al., 2006). By directly examining the wetting behavior of the oil and WMDF, F.B. Growcock and A. Belkin (2006) have found that whether the oil is applied to the drilling fluid or the fluid applied to the oil, the applied phase spreads over the substrate phase, i.e. the contact angle is very low(<5degrees).

These phenomena have close relations to the structure of micro-bubble. As fig. 2 shows, the hydrophilic ends of surfactants fixed in the “compatibility enhancing membrane” often have charges, which will cause electrostatic repulsion. Additionally, the viscoelasticity of “incompact zone” will not allow micro-bubbles in the WMDF to attach together but separate into bulk water automatically. The micro-bubbles were only made up of “air-bags” if the “incompact zones” were lost. That so many hydrophobic tails point to the outmost side will make the WMDF compatible with oil. Sometimes these bubbles can adsorb other micro-bubbles of the same structure and form congeries in different sizes. If the congeries only consist of several micro-bubbles, they can adsorb some LHP and surfactants in the bulk water to reconstruct the “incompact zones”, then perform as an individual micro-bubble. Although the congeries have more than one “gas core”, we still say that they are of the structure of “one core, two layers and three membranes” for the sake of describing conveniently. However, if the congeries consist of quite a large number of micro-bubbles and the pressure differences exist, congeries will expand and aggregate quickly toward the direction of pressure drop, thus forming a bubble band in the front of the fluid.

The micro-bubbles in WMDF will lose their “incompact zones” in the following three conditions. First, when WMDF moves at a very high speed, “incompact zones” will be held up in the bulk water for they have very good solubility and can be easily separated from “air-bags”. this can be seen when WMDF flows through drill pipes. Second, when passing the small openings which are smaller than micro-bubbles’ size, micro-bubbles will change their shapes or be cut into pieces and then lose “incompact zones”. When WMDF passes through fine screen, lineal split or narrow pore throat belongs to the case mentioned above. Third, if micro-bubbles expand sharply in a split second, concentration of LHP and surfactants in “incompact zones” will shrink to the level as it is in bulk water. This will happen when WMDF encounts large fractures or big caverns.

3.2 High Yield Stress Shear Thinning Property

Compared with bulk water, “incompact zones” hold a much higer concentration of LHP and surfactants, so they have more complicated networks. If networks are destroyed, reconstruction of “incompact zones” will be much quicker than in bulk water. WMDF has very high yield stress at an extreme low shear rate since networks in “incompact zones” will be damaged first, then reconstructed. With the shear rate increase, networks will be broken up more quickly until the rate of broke and reconstruction reach a balance in “incompact zones” and bulk water. If the shear rate is high enough, the WMDF will have very good fluidity because the rate of destruction of network is far quicker than reconstruction and LHP will improve the fluidity. What’s more, motived micro-bubbles will decrease viscosity of fluid (Sebba, 1987). Tom Brookey (1998) had determined the viscosity of WMDF and base fluid at different shear rates and had found the phenomenon described above.

4. MECHANISM FOR CIRCULATION CONTROL

Micro-bubbles can change their structures when passing openings of different sizes and that’s why WMDF can control circulation loss in different conditions. Micro-bubbles in WMDF are composed of “air-bags” and “incompact zones” at surface rightly after preparation. When the WMDF is pumping from mud pit to well, “incompact zones” of micro-bubbles will be damaged by high shear rate caused by flow, and will leave “air-bags” alone in bulk water. However, there are still a number of LHP and surfactants in bulk water, these “air-bags” will not attach to each other to form aggregation but to keep independently and flow with the WMDF if there is no pressure difference. With the depth increasing, “air-bags” will be compressed and will accumulate more energy because of the increase of pressure and temperature. Professor F.B. Growcock (2006) found that micro-bubbles can exist at 3000psi for a long time. Compressed micro-bubbles will expand to normal size and reconstruct their “incompact zones” when coming back to surface through annular if no lost circulation zones are encountered during the whole process. Otherwise, micro-bubbles will perform quite differently in accordance with different conditions as following description.

4.1 Encounter Large Fracture or Big Cavern

Take the large fracture for example, considerable pressure differences exist between annular and lost circulation zones and that will lead the micro-bubbles to expand sharply and move quickly to lower pressure areas, causing micro-bubbles to lose their “incompact zones” completely and aggregate together as a large unit of bubbles band blocking between annular and large fracture.

Bubbles’ flow appears to follow conventional Navier-Stokes theory (L.D. Landau ex tl., 1995). For a rigid sphere in a fluid is only affected by one-dimensional pressure gradient, $\triangle P/L$, the relative velocity of the bubble in an infinitely wide conduit is $V = 0.23\ r^2/\eta * \triangle P/L$, where r is bubble radius and η is the fluid viscosity. In this theory, large size bubbles will move faster and take up the front area. According to Laplace equation, the frontal bubbles will expand till there is a pressure balance between the front bubbles and formation. Anterior bubbles will restrain the latter bubbles’ expanding and reduce their moving velocity gradually. Little by little, bubbles near annular will not need to expand any more, and pressure between these bubbles and WMDF in annular will reach a balance. At that point, WMDF accomplishes the task of controlling circulation lost, and then goes upward to surface as normal. However, if the frontal bubbles are broken into pieces in the process of expanding, latter bubbles will go on expanding and blocking in the front until no bubbles need to expand any more. Just as fig. 3 shows.

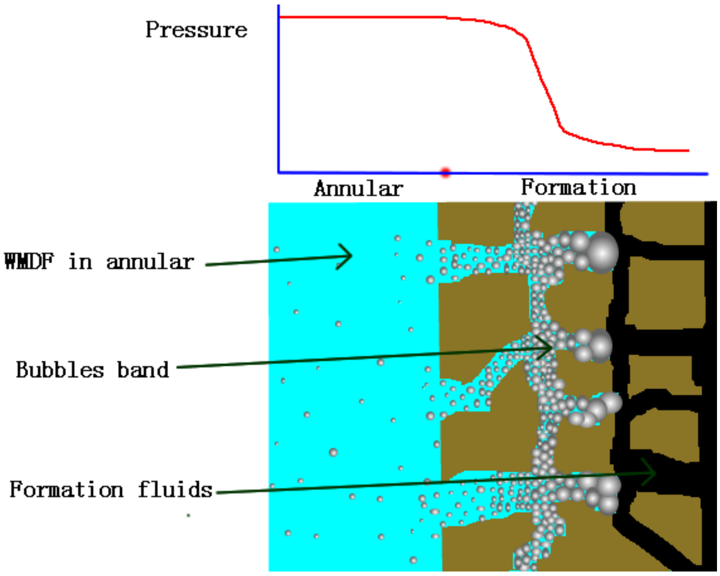

Fig. 3 Schematic of micro-bubble bridging macro-fracture

Actually, it is the “air-bags” that block the leakage zone while the WMDF is circulating. Because most of the formation rocks are water wetted, these hydrophobic “air-bags” will not stick to rocks. So, water in “high viscosity layer” will not enter into formation or enter in at a very low rate. Thus WMDF is able to circulate normally while micro-bubbles are blocking in the zone.

The first application of WMDF in West Texas (Tom brookey, 1998), where the bit dropped one foot, is very successful because the circulation can still be regained. Some laboratory experiments had been done to confirm the correctness of the explanation above. First of all, we design a specific formula using multiple regression method (Zheng lihui, 2008). Then test its sealing ability by measuring the filtration rate in 10 minutes conduct with sands of 80 screen mesh. All the results are put into table.1. From table.1 we can see that compared with the ordinary drilling fluid, WMDF can minimize the filtration rate effectively. With the pressure difference increase, its sealing ability will improve.

Table.1 sealing effect of WMDF

Pressure difference (MPa)	0	0.3	0.6	0.9	1.2
Ordinary drilling fluid (mL)	160	8000	10500	12000	13400
WMDF (mL)	0	4	3	0	0

Fig.4 is a real picture of the sealing experimental result of WMDF. We can clearly see that there is a departure of sands between bubble bands sealing region and remainder sands after the pressure difference is released.

Fig. 4 A real picture of sealing test

4.2 Encounter Rimula or Narrow Throat

Micro-bubbles will lose their “incompact-zones” while expanding rapidly under positive differential pressure. According to Navier-Stokes’ theory, the larger-sized micro-bubbles will come to the leakage zone first. These bubbles will change their shapes and sizes properly in order to enter into the throat. Sometimes, micro-bubbles can enter into the throat directly if the positive differential pressure is not large enough to destroy the bubbles. Hydrophobic “air-bags” in throat will cause capillary force which will prevent following micro-bubbles from expanding and will slow down their velocity. Accumulation of the capillary force will create great residence that will stop WMDF from coming into the zone. When the rate slows down, “incompact zones” will be reconstructed and viscosity of the system will increase sharply. High yield stress at an extremely low shear rate will also prevent WMDF from entering, as fig. 5 shows.

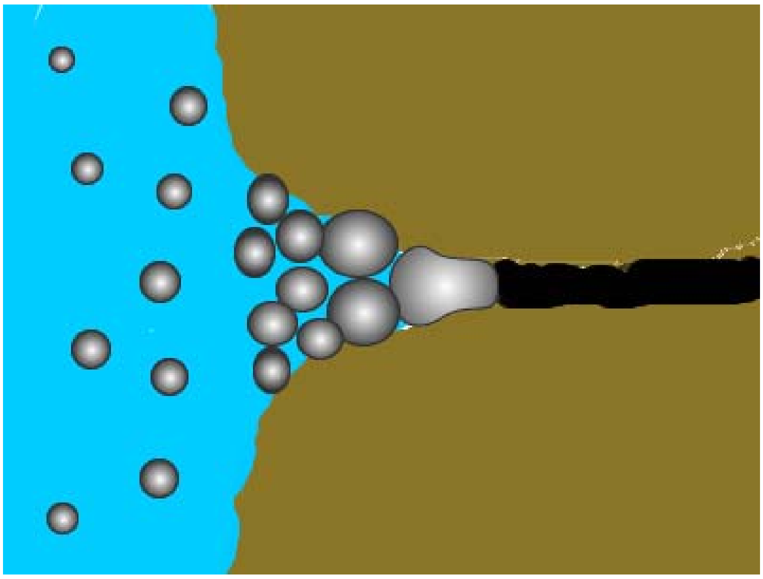

Fig. 5 Schematic of Micro-Bubble sealing narrow pore throat

However, if the positive differential pressure is very large, micro-bubbles will be destroyed or cut into fines before entering into the formation until the size is suitable to seal the throat. The mechanism for sealing is also the process of using capillary force mentioned above.

4.3 Encounter Percolation Zone

Though micro-bubbles can expand for bridging large fracture and sealing narrow throat, the expanded micro-bubbles can not enter into the percolation zone because the bubble size is too large compared with the percolation zone aperture. Fortunately, a great amount of polymer that creates high viscosity exists in the system. On the one hand, polymer slows down the rate of penetration by high viscosity. On the other hand, polymer will form the mud cake which effectively prevents WMDF from further entering.

In summary, micro-bubbles will adjust the size, shape or structure automatically according to the slot width of fracture, height of cavern or the aperture of openings to control lost circulation and help formation bearing larger pressure. While drilling a well with multiple pressured sequences, we can choose the WMDF system for the highest pressure zone. Bubbles will firstly seal the leakage zone which owns highest pressure difference with drilling fluid hydrostatic column. For the sealing bubbles are compressible and deformable, they can help sealed zones to bear higher pressure difference. Then, bubbles will automatically seal other leakage zones with less pressure differences until all of them are sealed, and the whole well will be drilled safely.

5. RHEOLOGICAL PROPERTY

The special structure of micro-bubble also makes WMDF have very good rheological property to meet the requirements of petroleum drilling industry. Table.2 is a series of formulas of WMDF designed by multiple regression and these systems' rheological parameters which are measured by rotary viscometer.

Table.2 rheological parameters of WMDF with different density

Density(g/cm^3)	Rheological parameter				
	PV (mPa s)	YP(Pa)	YP/PV	initial gel	Ten mins gel
0.81	17.00	23.51	1.38	8.18	10.73
0.91	25.00	30.66	1.23	8.18	10.73
1.02	31.00	39.35	1.27	9.71	13.29
1.12	22.00	32.19	1.46	10.73	13.80
1.18	20.00	38.33	1.92	10.99	16.35

These data reflect some important information. First of all, WMDF has very high viscosity no matter how high its density is. Plastic viscosity varies from 17 mPa s to 31 mPa s while the ordinary solids free water-based drilling fluids have the plastic viscosity ranging from 4 to 16 mPa s if they are of the same density of WMDF. Secondly, yield stress is extraordinarily high. Thirdly, the ratio of yield stress and plastic viscosity is much higher than any other drilling fluids. Table.2 shows each of them is over than 1.2 but the ratio of ordinary drilling fluids is controlled between 0.36 and 0.48. Fourthly, initial gel strength and final strength are very high. All of these are important for petroleum drilling.

For acceptable drilling fluids they must have abilities to clean the well, suspend the cuttings and weighting materials, keep the well wall stable and make sure it's safe while tripping. What's more, a good drilling fluid system should also increase the drill speed but not destroy the environmental balance. WMDF is the very system that meets these requirements.

In general, it is better to have a lower velocity of drilling fluids in annular to carry cuttings out of the well, and this will make sure that the drill bits have enough hydraulic horsepower to drill and enable the well wall to have stability because the returning rate will be not high enough to destroy the mud cake which sticks to the well wall. Reynolds number is often used to calculate the highest velocity which will not destroy the stability of well wall. It turns out that with the increase of PV and YP/PV the critical velocity will also be increased. So, from rheological view, high PV and YP/PV will prevent the WMDF system from turbulent flow and then ensure the stability of well. On the side, the high viscosity of WMDF makes it possible to carry drill cuttings out of well at low velocity. Additionally, high YP/PV will help the system turn to flat plate laminar flow which is in favor of carrying debris. Once the drilling process is stopped by the climate reasons or etc., network will be formed immediately and the gel strength will be strong enough to suspend the debris and weighting material to avoid sticking because WMDF has very high initial gel strength. The only thing that should be paid attention to is that if the WMDF stands still for some time, recirculation should begin with a small fraction of the system then the whole fluid system begins to recirculate. However, once the bubbles move, they will help to destroy the network structure formed by LHP and decrease the viscosity. Additionally, liner high polymers, the main agent of WMDF, are good flow pattern modifier which makes the system sheared thinning very well. On the one hand, this shear thinning system can avoid accident while tripping or pumping. On the other hand, it will increase the penetration rate in a great amount for it owns stronger impact force but less resistance while breaking the rocks.

6. CONCLUSION

Micro-bubble in WMDF has the structure of “one core, two layers and three membranes”. According to the different bond stress between membranes and layers, micro-bubble can be divided into two parts, structure stabled “air-bag” and dynamic changed “incompact zone”. Dynamic change of “incompact zone” is the radical reason why micro-bubbles can exist in WMDF independently or assemble together, why WMDF has very high yield stress at an extremely low shear rate but has good fluidity at an high shear rate, and why WMDF can wet both hydrophilic and hydrophobic surfaces.

It is the special structure that explains the mechanism for lost circulation control. However, if the formation rock is oil wetted, WMDF will lose its function. Fortunately, oil wetted rock is really rare. Some measurements indicate WMDF has high plastic viscosity, yield stress, YP/PV, initial gel and final gel which are important to meet the requirements of petroleum drilling.

What’s more, we can change the bond strength between different layers and membranes by choosing or synthesizing different agents to improve micro-bubbles’ stability, to enhance the system’s ability of antipollution and bearing high temperature. Thus, WMDF can meet requirements of different petroleum tasks like drilling, well completion, workover and so on. The range of application of WMDF will be enlarged.

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