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Research article

Development and application of ZM-2 drilling fluid density adjustment mixing device

Lei Zongming*, Rong Zhun, Kong Songtao

Chongqing University of Science & Technology, Chongqing, 401331, China

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Abstract

High-pressure shallow (gas/water) flow is often hidden in the deepwater seabed, so penetrating shallow flow in drilling without BOP will be highly risky. In this case, the conventional well killing method to balance the formation pressure with back pressure generated by well head equipment is no longer suitable. Based on the analysis of structural characteristics of domestic and foreign multi-phase mixing systems, a ZM-2 drilling fluid density adjustment mixing device with independent intellectual property right was developed according to the principles of dynamic well killing. The device is mainly composed of a throttle valve, a high-precision electromagnetic flowmeter, a mixer, dumbbell-shaped nozzles, connecting pipes and other components. Fixed on the mixer are three inlets to fill heavy mud, seawater and additives. Opposed jetting is adopted to realize rapid and uniform mixing of fluids with different densities. A laboratory test was conducted to work out the relationship between throttle opening and injection flow rate and establish a linear relationship between killing fluid density and heavy mud flow. The results of field test conducted in the Nanhai No.8 drill ship showed that the mixing device was stable in operation and excellent in mixing performance. The density difference of ingredient mixture could be controlled within 0.05 g/cm^3 after the mixture flowed out of the mixing chamber of the mixer of about 0.3 m long, so such high precision can meet the requirement of dynamic well killing.

Keywords: Mixing device; Killing fluid; Density; Flow field simulation; Nanhai No.8; Laboratory test; Field test; Dynamic well killing method

Compared with the drilling on land and in shallow water, deepwater drilling faces more complex sea conditions and more challenges, including unstable mud line, shallow geologic hazards, narrow density windows and harm of gas hydrate, which makes the deepwater drilling more risky and costly.

In order to control shallow water and other hazards, dynamic killing system is needed to achieve the rapid change of drilling fluid density and thus the adjustment of the annulus drilling fluid equivalent circulating density, so as to accurately control wellbore annulus pressure. Drilling fluid density adjustment mixing device is the key device of dynamic killing and drilling technology, its working principle is similar to the automatic cement-mixing principle in cementing operation. When necessary, the device can mix heavy mud prepared in advance with normal drilling or low-density drilling mud or seawater to get the mud density required quickly, thus realizing continuous pumping of drilling mud into the well. In this way, the formation fluid flowing into the wellbore can be effectively controlled and the complex kick or lost circulation can be reduced, increasing drilling efficiency and drilling safety, and fulfilling dynamic killing of drilling and increasing drilling fluid density side by side in the true sense [1–4].

1. Working principles and characteristics of ZM-2 drilling fluid density adjustment mixing device

1.1. Working principles

ZM-2 drilling fluid adjustment mixing device has two inlets: seawater inlet and heavy mud inlet. When kill operation

* Corresponding author.
E-mail address: lzmcust@126.com (Lei ZM).
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is needed, the throttle at the inlets can be adjusted to control the pumping rate of seawater and heavy drilling fluid respectively. After passing through different branch pipes and necessary parameters are measured by the electromagnetic flowmeter, seawater and heavy mud are jetted into the mixer through the nozzles, then under the action of shear mixing, the drilling fluid would reach good mixing effect at the outlet [5]. The drilling fluid from the export pipeline can be directly sent to mud pump for well killing, replacing the conventional method of seawater drilling and heavy mud bullheading.

During drilling operation, the opening of the throttle valves at the inlets can be adjusted in time to change the pumping rate of seawater and heavy mud according to the monitored formation pressure. The drilling fluid needed can be pumped out at the outlet of the device to keep wellbore pressure in between the formation pore pressure and fracture pressure [6]. The basic process is shown in Fig. 1.

During dynamic kill drilling, the friction resistance of borehole killing fluid plus liquid column pressure should be slightly higher than the pore pressure and lower than fracture pressure. When shallow flow is encountered, killing fluid of required density must be pumped into the annulus at the pre-calculated rate as quickly as possible to kill the well.

According to the special conditions of offshore drilling, killing fluid density should be dynamically determined by the shallow flow formation pressure, formation fracture pressure, and wellbore circulating friction, etc. The ratio of heavy mud and seawater is calculated with the following formula.

$$\begin{cases} Q = Q_1 + Q_2 \\ \rho_1 Q = \rho_0 Q_1 + \rho_{SW} Q_2 \end{cases} \tag{1}$$

Where, ρ_0 is heavy mud density, g/cm^3; ρ_1 is drilling fluid density in dynamic well killing, g/cm^3; ρ_{sw} is seawater density, g/cm^3; Q is the required pumping rate of killing fluid, L/s; Q_1 is the pumping rate of heavy mud, L/s; Q_2 is the pumping rate of seawater, L/s.

When the required pumping rate of killing fluid is known, the pumping rate of heavy mud and seawater can be worked out with the above formula. Finally the minimum pumping rate of killing fluid should meet the requirements of cutting-carrying, and the maximum pumping rate should meet the conditions to keep borehole wall stable and avoid circulation loss simultaneously [5,6].

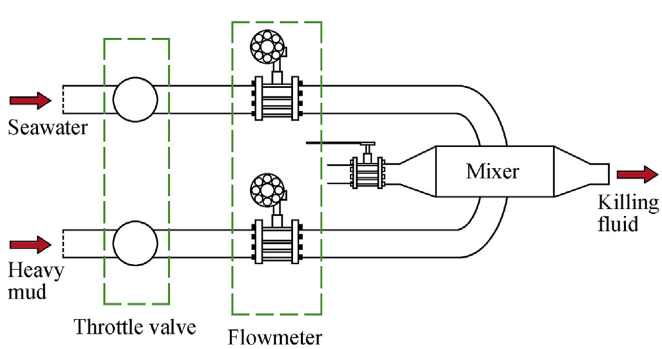

Fig. 1. Process chart of ZM-2 drilling fluid density adjustment mixing device.

1.2. Structure and components

ZM-2 drilling fluid density adjustment mixing device, mainly composed of connecting line, throttle valve, high precision electromagnetic flowmeter, mixer, and dumbbell nozzle, functions to realize the rapid change of drilling fluid density. It comprises a tubular mixer which has a heavy mud inlet and a seawater inlet connected by an interface each on its circumference, at the other end a mixture outlet, in the center of each interface installed a nozzle of dumbbell-shaped cross section through a throat, and the two nozzles are 90° staggered. The center axis of the two interfaces coincides, and the nozzle jet direction is perpendicular to the axis of the mixer body [7,8]. At one end of the mixer, an inlet for additives is reserved; when necessary, three phases (seawater, heavy mud and additive) can be mixed simultaneously.

1.3. Mixing mechanism

In order to make the three-phase fluid mix evenly in the mixer, in view of the drilling fluid mixer, since viscous base fluid flow forms may include laminar flow, transition zone and turbulent flow, therefore, mixing mechanisms of laminar flow and turbulent flow must be considered in the mixer, that means in laminar flow, the regular and repeated “splitting – resetting – re-merging” works on the fluids to mix them, while in turbulent flow, besides considering the above three elements, because of the strong eddy currents formed by fluid on the flow section direction, strong shear force would act on the fluid, cutting and mixing the fine part of the fluid further [9–11].

This device uses nozzles with dumbbell-shaped cross section, by staggering the two high-speed low-pressure fluid flow jetted out of the two nozzles, and producing shear mixing at the low speed area in the mixer, strong turbulence would occur around the nozzles, in full compliance with the turbulence flow characteristics, so three-dimensional Navier–Stokes equations can be taken as the governing equations, and the standard k-ϵ two-equation turbulence model can be selected to set up a closed control equation system.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \tag{2}$$

$$\rho \frac{\partial v}{\partial t} = \rho \overrightarrow{f} - \nabla P + \mu \nabla^2 v \tag{3}$$

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k v)}{\partial x_i} = P - \rho\epsilon + \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{C_\mu \rho k^2}{\sigma_k \epsilon}\right)\frac{\partial k}{\partial x_i}\right] \tag{4}$$

$$\frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial(\rho \epsilon v)}{\partial x_i} = C_{\epsilon 1}\frac{\epsilon}{k}P_t - C_{\epsilon 2}\rho\frac{\epsilon^2}{k} + \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{C_\mu \rho k^2}{\sigma_\epsilon \epsilon}\right)\frac{\partial \epsilon}{\partial x_i}\right] \tag{5}$$

Where, k, ϵ, v, ρ, μ, P and $\overrightarrow{f}$ are the turbulent flow energy, turbulent flow rate, velocity, density, turbulence viscosity coefficient, pressure and unit weight respectively, and

$C_{\epsilon 1} = 1.44$, $C_{\epsilon 2} = 1.92$, $\sigma_\epsilon = 1.3$, $\sigma_k = 1.0$, $C_\mu = 0.09$. The finite volume method was used to solve three-dimensional $N-S$ equations of incompressible fluid with different densities, and the mixing mechanism was examined with numerical simulation [12].

1.4. Main technical characteristics

1) ZM-2 drilling fluid density adjustment mixing device mixes fluid in an counterflow manner, and in each inlet throat connected with the mixer body installed a nozzle with dumbbell-shaped cross section, and the two nozzles are staggered at 90°, which makes the grain size of the mixed components smaller and mixing precision higher.
2) In the center of the mixer an additive inlet is reserved, which allows the mixing of water, heavy mud and additive, to get the drilling fluid with the required density and rheological properties, and to continuously pump the drilling fluid to the borehole so as to make killing fluid density in between the formation pore pressure and fracture pressure.
3) ZM-2 drilling fluid density adjustment mixing device has the advantages of small size and convenient installation, and can realize the mixing of high rate and high precision. The maximum displacement can be up to 80 L/s, and mixed component density differences can be controlled under 0.05 g/cm^3 after the mixture is about 0.3 m away from the mixing chamber.

2. Numerical simulation of flow field

The fluid flow in the drilling fluid mixer is complex and variable. Its field test is difficult and costly. But the flow field of three-dimensional turbulent viscous flow in the mixer can be simulated with CFD software to answer some practical questions.

2.1. Two-phase flow simulation

Heavy mud and water were pumped into the mixer from the two inlets on the mixer circumference continuously, and the density distribution of the mixture was observed.

The case in which two nozzle interface axis at the main mixing device body was staggered 90°, and the jet nozzle axis direction was perpendicular to the direction of the axis of mixing device body was simulated. The simulation conditions are: the density of seawater injected was 1.03 g/cm^3, the density of heavy mud was 1.93 g/cm^3, the water displacement was 35 L/s, the heavy mud displacement was 15 L/s. It can be seen from the density distribution map (Fig. 2) that when two fluids at different flow rate were jetted through the nozzles at 180°, they were staggered, and shear mixing occurred in the low speed region of the mixer, making the mixed components smaller in grain size and blend more evenly.

The total length of the simulated mixer was 1000 mm. It can be seen from the density change chart that density tends to be stable after the mixed liquid flows about 300 mm out of the mixer (Fig. 3), mixed component density difference can be controlled within 0.05 g/cm^3. It is concluded from analysis that the design is reasonable.

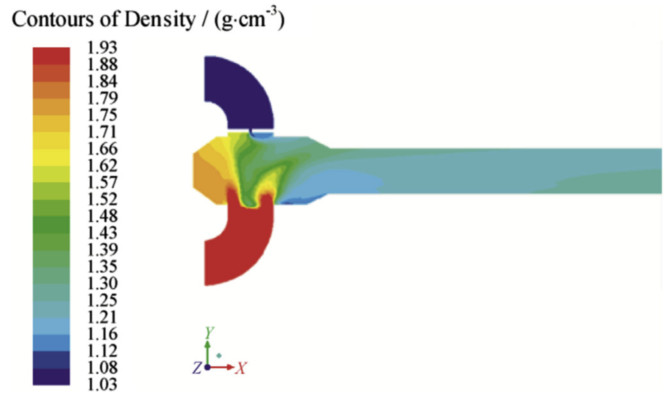

Fig. 2. Cloud picture of density distribution.

2.1.1. Three-phase flow simulation

When three-phase flow was simulated, besides heavy mud and seawater, another inlet at the central axis of the mixer was added for additive. The simulation conditions are: the density of seawater injected into the mixer was 1.03 g/cm^3, the density of heavy mud was 1.93 g/cm^3, the density of additive was 1.1 g/cm^3, the water displacement was 35 L/s, the

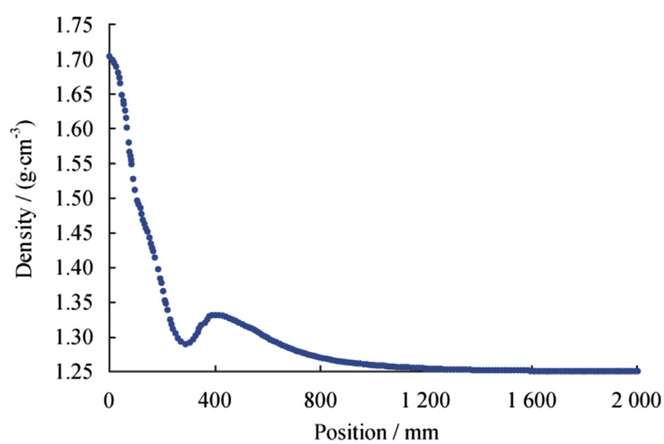

Fig. 3. Density changes of the mixed fluid.

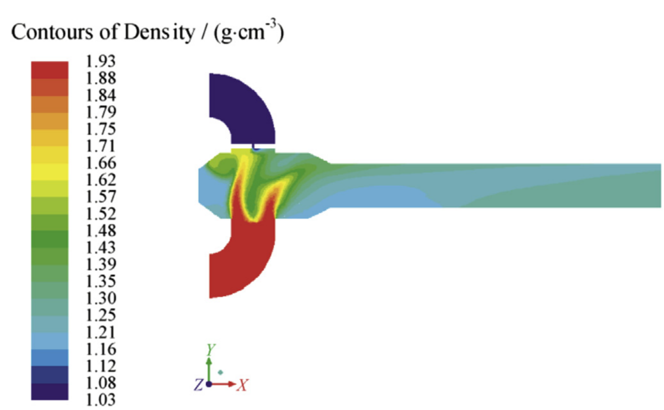

Fig. 4. Cloud picture of three-phase density.

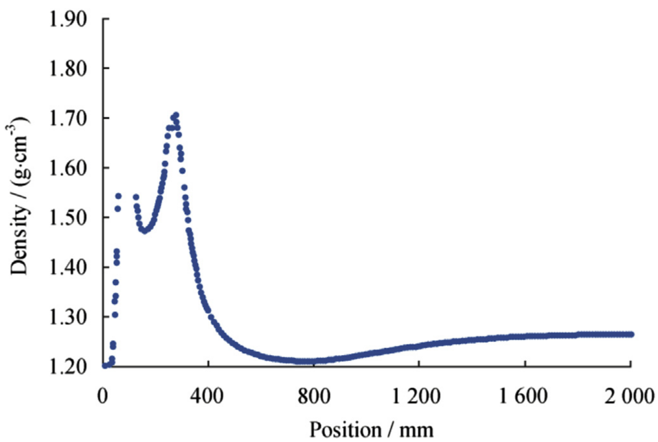

Fig. 5. Three-phase density change coordinate graph.

Table 1
Mean square deviation of drilling fluid density at the outlet.

S/N	Inlet displacement L s^{-1}	Mean square deviation of drilling fluid density at the outlet
1	16	0.68%
2	25	0.2%
3	34	0.05%
4	43	0.02%
5	52	0.3%
6	61	0.58%
7	70	1.2%

displacement of heavy mud was 15 L/s, the displacement of additive was 8 L/s.

It can be seen that there is not much difference between three-phase and two-phase mixing, both resulting in even mixture (Fig. 4). But the coordinate diagram of three-phase density changes (Fig. 5) shows that the density of the mixture became stable at a place of 1500 mm out of the mix chamber, 200 mm longer than the two-phase mixture, but both mixing was complete within a length of 1600 mm, thus, the device works well in mixing three-phase fluids too.

2.2. Influence of inlet flow rate on mixing effect

Simulation conditions are: the density of seawater injected into the mixer was 1.03 g/cm^3, density of heavy mud was 1.93 g/cm^3. When seawater and heavy mud were injected into the mixer at the displacement of 16–70 L/s through the dumbbell-shaped nozzle, and mixed in the mixing chamber, the mean square deviation of drilling fluid density at the outlet is shown in Table 1.

Table 1 shows that the mean square deviation of drilling fluid density at the outlet is generally less than 2%. Under a normal working condition, the inlet displacement has little impact on the mixing effect, so the mixer can fully satisfy engineering requirement.

3. Commissioning test of the mixing device

3.1. Laboratory test

3.1.1. Test methods

The flow rate of seawater and heavy mud directly affect the density of the mixed drilling fluid, through the adjustment of the throttle opening degree and observation of the flowmeter reading, the relationship between the throttle valve's opening and density of the mixed drilling fluid can be figured out.

3.1.2. Test results

While one inlet was closed, the pump was turned on, and the opening of throttle valve was adjusted. The instantaneous flowmeter readings were recorded at 30 s interval, and the cumulative flow rate was recorded too (Table 2).

The experiment showed that the flow rate is proportional to the throttle valve's opening, and with the increase of the throttle valve's opening, the increase of flow rate decreases. In actual operation, the opening of throttle valve at seawater and heavy mud inlets can be adjusted to control the drilling fluid density at the outlet, realizing dynamic kill drilling.

3.2. Field test

In order to verify the function, stability and reliability of ZM-2 drilling fluid density adjustment mixing device, relevant tests were carried out on “Nanhai No.8” drilling ship. The results show that the device works stably and reliably, and can quickly and accurately adjust drilling fluid to the required density.

3.2.1. The testing process

The 40 m^3 drilling fluid of 1.30 g/cm^3 was prepared in advance, and then the displacement of heavy mud and diluent at the planned test displacement was worked out by using the formula. 5 # pool was emptied of drilling fluid and flushed with seawater; according to the calculation results, the DKD equipment's displacement of seawater and heavy mud was adjusted, the mixed drilling fluid reached above the stirrer surface of 5 # pool (in the mixing process, the stirrer of the reserve liquid pool remained open), without waiting for stirring, a drilling fluid sample was taken from 5 # pool for direct measurement; a few minutes later, another sample was taken for measurement to get the actual measured value.

Table 2
Relationship between throttle valve's opening and flow rate.

Times	1	2	3	4	5	6	7	8	9
Opening/(°)	90	60	45	30	20	30	45	60	90
Instantaneous flow rate (L/s)	193.3	190.8	182.5	164.3	127.1	142.6	181.8	189.3	192.7
Average flow rate (L/s)	259.5	189.2	171.2	152.7	119.5	134.0	191.8	174.8	205.2

Table 3
Dynamic kill heavy mud mixing test data table.

Displacement (L/s)	The density of diluent (g/cm^3)	The density of heavy mud (g/cm^3)	The density of kill mud (g/cm^3)	The displacement of diluent (L/s)	The displacement of heavy mud (L/s)	The measured density (g/cm^3)
235	1.03	1.30	1.10	174.074	60.926	1.100
235	1.03	1.30	1.12	156.667	78.333	1.120
235	1.03	1.30	1.14	139.259	95.741	1.140
235	1.03	1.30	1.16	121.852	113.148	1.155
235	1.03	1.30	1.18	104.444	130.556	1.180
235	1.03	1.30	1.20	87.037	147.963	1.200

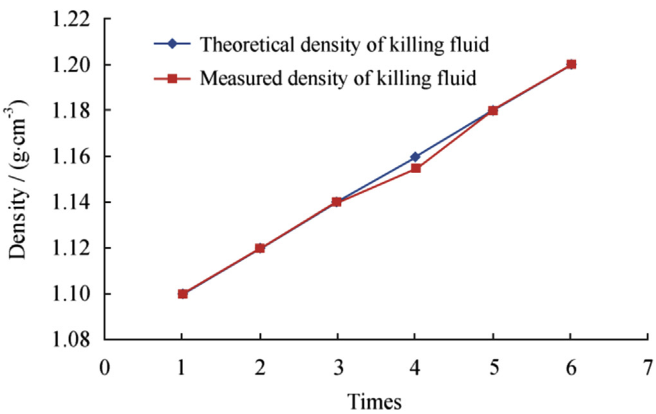

Fig. 6. Comparison of well killing fluid density curves.

3.2.2. The test results

The test data show that the mixing effect of the device is good, with a mixed density error of less than 1% (Table 3), and killing fluid density has a linear relationship with the heavy mud flow rate (Figs. 6 and 7). When diluent density and heavy mud density are known, the required killing fluid density can be obtained through the adjustment of the flow rate of heavy mud and diluent.

4. Conclusions

Through the study of the drilling fluid density adjustment mixing device, we reached the following conclusions:

1) ZM-2 drilling fluid density adjustment mixing device can quickly and effectively mix drilling fluids and control the wellbore fluid column pressure accurately, avoiding the borehole collapse caused by excessive drilling fluid density, and ultimately making the kill operation in wells with narrow safety window more secure.
2) The flow field numerical simulation and field test show that the mixture density error can be controlled below 0.05 g/cm^3 after the mixture reaches at a place of about 0.3 m out of the mixing chamber, so the precision is high enough to meet the drilling operation requirement.
3) According to the measured formation pressure from formation pressure monitoring during drilling, the required drilling fluid density and mud pump displacement can be worked out in real time. And then the volume and density of prepared drilling fluid in the mud pit are adjusted and the drilling fluid injection time is controlled to realize dynamic well killing.

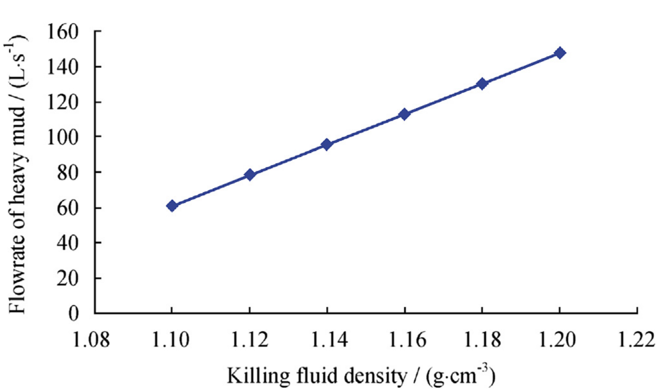

Fig. 7. Relationship of well killing fluid density and heavy mud flow rate.

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