DYNAMIC UNDERBALANCED DRILLING TECHNIQUE

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ABSTRACT

Overbalanced drilling (OBD) is known to be cheap and simple but formation damage and reduced rate of penetration (ROP) are some of its disadvantages. However, underbalanced drilling (UBD) minimizes formation damage and achieve high ROP, but it is expensive, complex and can’t be applied in many cases.

This application introduces a new technique that incorporates the advantages and avoids the disadvantages of these drilling systems and is referred to as Dynamic Underbalanced Drilling (DUBD).

In DUBD a pressure drop at the environ of the bit, below and around, is created that is restored to normal pressure above the bit and such conditions requires some minor modifications to the design of drill bit. Thus at the zone located below and around the bit underbalance conditions are dominated while the rest of the hole is overbalanced.

The anticipated cost of this technique is nearly zero and it is expected to save much of drilling costs. DUBD is expected to provide higher ROP that may exceed ordinary UBD in some cases, so saves time, reduce formation damage, saves costs (cheaper than OBD) and enables gathering information about the reservoir while drilling. This can save some of logging and testing costs. In addition, DUBD may reduce drilling problems, particularly time sensitive problems, and overcome problems of UBD. Furthermore, it can be used safely in over pressurized shale and salt formations, where UBD is not recommended.
Convention direction

Conventional nozzle orientation

Fig. 2
Stagnation zone where all dynamic head is restored to pressure
Fig. 4
Fig. 5
Fig. 7
Fig. 8
Fig. 10
Required nozzle orientation

% of total costs saved

Fig. 11
% of total days saved

- %
- 0% 5% 10% 15% 20% 25% 30% 35% 40% 45%
- Multiples of ROP
- Fig. 12
Fig. 13
The often cited example of the Bernoulli Equation or "Bernoulli Effect" is the reduction in pressure which occurs when the fluid speed increases.

Increased fluid speed, decreased internal pressure.

The energy equation for this scenario is:

\[ P_1 + \frac{1}{2} \rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2} \rho v_2^2 + \rho g h_2 \]
Fig. 16

Desired flow direction

Conventional nozzle orientation

Required nozzle orientation
Desired flow direction

No stagnation point below bit
<table>
<thead>
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<th>Pressure drop (psi)</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
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<td>2,476.6</td>
<td>3,234.8</td>
<td>4,094.0</td>
</tr>
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</table>

\[
\Delta P(\text{psi}) = 8.08153 \times 10^{-4} \rho(\text{ppg})v^2(\text{ft/sec})
\]

\[
\Delta P(\text{psi}) = 1.07875 \times 10^{-4} \rho(\text{lb/ft}^3)v^2(\text{ft/sec})
\]
pressure drop due to various velocities for various specific gravities

![Graph showing pressure drop vs. fluid velocity for different specific gravities.]

Fig. 21
\[ \log \left( \frac{R}{R_0} \right) = -m(P_{bh} - P_f) \]

Where:

- \( R \) = ROP,
- \( R_0 \) = ROP at zero overbalance,
- \( P_{bh} \) = bottom hole pressure,
- \( P_f \) = formation fluid pressure,
- \( m \) = line slope

\( (P_{bh} - P_f) = 0.052 H (\rho_c - \rho_p) \)

Where: \( H \) is the depth in feet

\[ \log \left( \frac{R}{R_0} \right) = -0.052 m H (\rho_c - \rho_p) = 0.052 m D (\rho_p - \rho_c) \]

\[ \log \left( \frac{R}{R_0} \right) = a_4 H (\rho_p - \rho_c) \]

Fig. 22
DYNAMIC UNDERBALANCED DRILLING TECHNIQUE

TECHNICAL FIELD

[0001] Petroleum industry (oil well drilling)

BACKGROUND ART

[0002] Conventional well drilling in petroleum industry uses drilling fluids with densities high enough to exceed formation pressure (this is known as over balanced drilling (OBD)). This enables the control of formation pressure to drill safely. However this method has disadvantages including damaging the producing formation, causing differential sticking, loss of circulation and reducing drilling rate or rate of penetration (ROP). To overcome these disadvantages Under Balanced Drilling (UBD) technique may be used. In UBD drilling fluids are lighter to keep pressure lower than formation pressure and this has many advantage including high ROP, eliminating differential sticking, minimize formation damage and no fluid losses. The disadvantages of UBD include high cost, complex operations and not applicable in all wells. Although UBD is useful in drilling depleted reservoirs and where complete loss may occur but for pressurized shale or high pressure formations, UBD cannot be used.

DISCLOSURE OF INVENTION

[0003] The Dynamic Under Balanced Drilling (DUBD) is based on general and basic physical laws such as conservation of mass and energy laws. In (DUBD) presented here, the under balance is not created by low fluid density as in UBD but by fluid velocity. Drilling fluid exits bit nozzles with high velocities and according to general energy equation (Bernoulli equation) the pressure will drop. This is mathematically expressed as:

\[
\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + Z_1 = \text{constant}
\]

Or:

\[
\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + Z_2
\]

[0004] When one type of energy increases (or decreases) in a closed system, one or more types of energies must decrease (or increase) so that the total of all energies remains the same (in the absence of external forces acting on the system). Thus, increasing fluid velocity will increase fluid kinetic energy, and this will lead to a decrease in pressure (elastic potential energy) only because elevation (potential energy) is the same for that point (depends on elevation), so increasing velocity will decrease pressure at the same point by an amount proportional to the square of fluid velocity, but this does not occur while drilling, why?

[0005] In OBD the nozzles are generally directed downward to provide high impact force and high bit hydraulic horsepower for hole cleaning. But this orientation will cause the drilling fluid to hit the bottom of the hole perpendicularly or near perpendicular. So the velocity at the bottom of the hole is reduced to zero (the fluid hits the formation and stops then flow in the reverse direction) at the formation being drilled. This converts all the kinetic energy to pressure so increases pressure at the formation and reduce ROP. In order to utilize the high velocity we must modify the nozzle orientation and size. Bit profile should be changed also so that the fluid exits the nozzles parallel to the formation so the pressure is reduced. This may be achieved by many designs. Simple designs will be shown below.

[0006] The DUBD simply is utilizing the very high fluid velocity caused by the used nozzles to lower the pressure so create an underbalanced zone below and around the bit. When the fluid then enters the larger area in the annulus above the bit, velocity is greatly reduced, so pressure rises again. See FIGS. 1 & 2.

[0007] The pressure drop due to the DUBD can be calculated as follow:

[0008] Bernoulli equation is suitable for our use if we add a term to account for losses in the system. We will compare between two points at the same depth. The only difference between the two points is the nozzle orientation. The first point is a point on the bottom of the hole with perpendicular nozzles. The second is the same point with DUBD bit modifications. The number 1 is for subscribing the first point and 2 for the second point. The two points are compared first to a point above the bit inside the drill string. This point is subscribed with a. Applying the general energy equation between point (1 and a), (2 and a) and (1 and 2).

\[
\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + Z_1 + H_\text{losses} = \frac{P_a}{\rho g} + \frac{v_a^2}{2g} + Z_a
\]

[0009] \( P \): pressure

[0010] \( g \): is the gravitational acceleration

[0011] \( \rho \): is the density

[0012] \( Z \): is the height above some reference plan

[0013] \( H \): is the head losses

\[
\frac{P_2}{\rho g} + \frac{v_2^2}{2g} + Z_2 + H_\text{losses} = \frac{P_a}{\rho g} + \frac{v_a^2}{2g} + Z_a
\]

[0014] The right hand side is the same in the two equations. \( H_\text{losses} \) is the same in the two equations because there is no difference except for nozzle orientation.

\[
\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + Z_2
\]

[0015] Now \( v_1 \)-zero since fluid will hit the bottom and velocity will decrease to zero. \( Z_1-Z_2 \) since the points are at the same elevation.

\[
\frac{P_1}{\rho g} = \frac{P_2}{\rho g} + \frac{v_2^2}{2g}
\]

\[
P_1 = P_2 + \frac{1}{2}\rho v_2^2
\]

\[
P_1 - P_0 = \frac{1}{2}\rho v_2^2
\]

\[
\Delta P = \frac{1}{2}\rho v_2^2
\]

[0016] This means that the pressure is reduced by an amount equal to 0.5 \( \rho v^2 \). Because velocity is very high, the pressure drop is very very high. For example, pressure drop exceeding 1,000 psi when fluid velocity is 350 ft/sec with specific gravity of 1.3. The following table shows the pressure drop due to various mud specific weights and fluid velocities.
<table>
<thead>
<tr>
<th>Pressure drop (psi)</th>
<th>velocity (ft/sec)</th>
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</thead>
<tbody>
<tr>
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<td>16.8</td>
</tr>
<tr>
<td>100</td>
<td>67.4</td>
</tr>
<tr>
<td>150</td>
<td>151.6</td>
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<tr>
<td>200</td>
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<td>300</td>
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<td>1,078.3</td>
</tr>
<tr>
<td>450</td>
<td>1,364.7</td>
</tr>
</tbody>
</table>

Specific gravity 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9 3.0 3.1 3.2 3.3 3.4 3.5 3.6 3.7 3.8 3.9 4.0 4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 4.9 5.0

16.8 18.5 20.2 21.9 23.6 25.3 27.0 28.6 30.3 32.0 33.7 35.4 37.1 38.8 40.5 42.2 43.9 45.6 47.3 49.0 50.7 52.4 54.1 55.8 57.5 59.2 60.9 62.6 64.3 66.0 67.7 69.4 71.1 72.8 74.5 76.2 77.9 79.6 81.3 83.0 84.7 86.4 88.1 89.8 91.5 93.2 94.9 96.6 98.3 100.0 101.7 103.4 105.1 106.8 108.5 110.2 111.9 113.6 115.3 117.0 118.7 120.4 122.1 123.8 125.5 127.2 128.9 130.6 132.3 134.0 135.7 137.4 139.1 140.8 142.5 144.2 145.9

0017 This pressure drop is the amount of pressure reduced below normal mud pressure at the bottom of the hole. If this technique is used with light fluids as that used in UBD the reduction in pressure may cause pressures near atmospheric at bottom of the hole. This leads to higher penetration rates than that in normal UBD techniques.

0018 From the above table, the amount of pressure drop for a given mud weight is determined by the fluid velocity. Fluid velocity is controlled by flow rate or nozzle size. So, not only a modification of nozzle orientation is required, but also nozzle size modification may be required. Bit profile is allowed to modify the modifications of nozzle and to keep velocity high without decreasing fluid velocity considerably. The number of changes available in design is too many, but the same basis must be maintained.

0019 Some benefits gained by this technique:

0020 Higher ROP that will reduce drilling time and costs as follow:

0021 Higher ROP means lower drilling days so cost is lowered.

0022 Higher ROP means lower open hole time so lower mud losses, hole problems and formation damage.

0023 Reservoir data can be obtained while drilling. These data include:

0024 Reservoir permeability (effective permeabilities)

0025 Reservoir pressure

0026 Fluid types

0027 Fluid distribution and saturation

0028 Extended bit life

0029 Better hole cleaning

0030 Increase reserve

0031 Can be used in almost all cases

0032 Some explanations of benefits:

0033 Increase in ROP:

The relation is:

\[ \log\left(\frac{R}{R_0}\right) = -m(P_{bh} - P_f) \]

Where:
- \( R \) = ROP,
- \( R_0 \) = ROP at zero overbalance,
- \( P_{bh} \) = bottom hole pressure,
- \( P_f \) = formation fluid pressure,
- \( m \) = line slope

By extrapolating this relation for under balance we got the following table for certain field:

<table>
<thead>
<tr>
<th>Overbalance difference (+ or -)</th>
<th>Multiple of decrease in ROP if OB increases</th>
<th>Multiple of increase in ROP if OB decreases</th>
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<td>1,500</td>
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<td>1,000</td>
<td>0.216</td>
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<tr>
<td>50</td>
<td>0.93</td>
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Thus if the DUBD creates 1,000 psi pressure drop the ROP is expected to be 4.6 times the ROP for normal operations. Using smaller nozzle sizes we can get more and more increase in ROP.

This increase in ROP will decrease cost and time considerably as shown below for four wells:
Great reduction in time and cost are observed for the four wells. This reduction calculation is based only on ROP increase for these wells. Cost and time reductions due to other benefits such as testing and logging time aren’t calculated here. We may eliminate the whole logging costs because while drilling we will know very much about the reservoir, so no need for extra logging costs or testing costs.

This increase in ROP will also reduce mud losses as the time where mud is lost to formation is reduced substantially. This means saving chemicals and costs, lowering environmental issues, and reducing formation damage. Reducing formation damage means lower stimulation costs and increase in recovery because abandonment pressure will be lowered with less damaged formation.

Because most hole problems are time dependent, so drilling the open hole section in a short period of time (while keeping excellent hole cleaning) will eliminate many open hole problems and saves time and cost.

Reservoir Data:

By modifying the bit profile we can keep the dynamic pressure drop around the bit. Since bit profile height is known, we can find so many reservoir data. For example we can determine permeability as follow:

If we circulate with certain rate and create underbalanced zone below and around the bit, formation fluid will enter the well as if the well is producing at that value of bottom hole pressure. Once the system is stabilized we will start record the volume and type of gain (oil, water, and gas) and let this continue for a certain period of time. Then we will alter the amount of underbalance created and wait for stabilization and start recording like the case in the lower underbalance. We repeat this for more degrees of underbalance. Then we take these data to Darcy equation.

For simplicity we will consider here the bit is off bottom and the flow is radially and try to detect permeability.

(Computer programs for the real case where flow is from around and below the bit may be used to detect permeability (both vertical and horizontal if the well is vertical or in two perpendicular directions in other wells).)

Q_i = \frac{2\pi h K_{wi} (P_e - P_{wf})}{\mu_i \ln \frac{r_{wi}}{r_{m}}}

OR

Q_i = \frac{2\pi h (P_e - P_{wf})}{\mu_i \ln \frac{r_{wi}}{r_{m}}} K_{wi}

OR

Q_i = \text{Constant} \times \mu_i

Where:

Q_i: flow rate of fluid i (water, oil or gas).

h: Pay zone thickness (bit profile elevation).

K_{wi}: effective permeability for fluid i (in this interval of reservoir).

P_e: Pressure at reservoir boundary (can be calculated also as will be shown later).

P_{wf}: Pressure at bottom of the well (calculated from the DUBD technique).

r_{wi}: reservoir radius (from geological data and other wells).

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Q_i = \frac{2\pi h K_{wi} (P_e - P_{wf})}{\mu_i \ln \frac{r_{wi}}{r_{m}}}

OR

Q_i = \frac{2\pi h (P_e - P_{wf})}{\mu_i \ln \frac{r_{wi}}{r_{m}}} K_{wi}

OR

Q_i = \text{Constant} \times \mu_i

Where:

Q_i: flow rate of fluid i (water, oil or gas).

h: Pay zone thickness (bit profile elevation).

K_{wi}: effective permeability for fluid i (in this interval of reservoir).

P_e: Pressure at reservoir boundary (can be calculated also as will be shown later).

P_{wf}: Pressure at bottom of the well (calculated from the DUBD technique).

r_{wi}: reservoir radius (from geological data and other wells).

So a good indicator of permeability is obtained by simple calculations and simply change flow rate. Thus the relative permeability is calculated.

Thus we got reservoir fluids and fluid distribution (from repeating this for the next h's in the well), reservoir pressure, effective permeability, thickness (Calculating how many h's are producing) and many other data by simple methods and calculations while drilling.

Extended Bit Life

Bit life is increased just like bits drilling in UBD.

Better Hole Cleaning

The hydraulics in DUBD provide better cleaning of the cuttings from the bottom by making the flow direction the same as the cutting path to surface. The cuttings will be entrained with the high velocity fluid. Fluid will enter the micro-fracks in the rock, widen it and eventually carry cuttings to the surface. No bit balling possibility. Hole cleaning depends here on:

- Fluid rheology
- Fluid velocity
- Buoyancy force
- Drag forces
- Increase Reserve

Lowering formation damage increases recoverable hydrocarbon. Also reduction in drilling costs and time will allow drilling more wells and depleting the reservoir with more wells, so recovery increase.

Can be used in almost all cases. It can be used if pressurized shale, salt domes or other high pressure formations are encountered.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1: As shown in the figure placing the nozzles in the center (white circle) of the bit and rotating them 90 degree (points radial outward i.e. the nozzle axis parallel to the arrows) so that the fluid will flow around the bit profile as shown by the blue arrows. This is one possible PDC bit designs that matches the DUBD requirements.
FIG. 2: As shown in the above figure, a possible design for DUBD in roller cone bits can utilize the extended bit nozzle to provide the required flow path. The nozzles are directed so the fluid will flow as shown by the blue arrows.

The two figures show two designs to be applied in DUBD. There are too many designs to do so and can be used in DUBD.

1: The Dynamic Underbalanced Drilling (DUBD) technique is based on the following modifications on drill bit:

1—Modifying nozzle orientation:

The nozzles are oriented in a direction so that the flow is parallel to the formation or don’t hit formation and keep the fluid velocity high in this zone. Two designs are given in the drawings. There are too many designs that can do the same target but one was mentioned for explanation.

2—Modifying nozzle size

The size of the nozzle is selected to provide the maximum suitable fluid velocity for the well or to reach a selected fluid speed to create the required pressure drop as in the table in the explanation part.

3—Modifying bit profile

To keep fluid velocity around and below the bit high. Flow area around the bit must be decreased with increasing number of blades for example or width of blades of the bit so the velocity is kept high. Also to provide smooth path for the fluid to flow parallel to the formation being drilled.

These modifications will according to general energy equation or Bernoulli equation create a pressure drop.

2: According to claim 1: These modifications are made to keep drilling fluid velocity high below and around the bit to create an underbalanced zone there to achieve the benefits mentioned below:

1—Increase ROP
2—Decrease drilling cost and time
3—Decrease formation damage
4—Get earlier data about the reservoir
5—Reduce drilling problems and drilling fluid losses
6—Provide better hole cleaning.

As mentioned in the explanation part:

The increase in ROP (as discussed earlier) is very great and is due to the created dynamic underbalance below and around the bit.

As ROP increases the time required for drilling will decrease and thus the cost will be decreased also.

Because formation will be subjected to the drilling fluid for shorter period of time so damage will be reduced greatly.

The technique allows getting information about reservoir while drilling. These data include (permeability, reservoir pressure, fluid types and distribution, . . . ) as mentioned in the explanation

Reducing open hole time will reduce drilling problems because most of them are time dependent. They increase if open hole time increases. Also the total fluid lost to the formation will be lower due to lower time for these losses. This technique improves hole cleaning as was discussed earlier.

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