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PREDICTION OF PRESSURE DROP REQUIRED FOR SAFE UNDERBALANCED DRILLING

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1. ABSTRACT

Many benefits can be gained by the application of underbalanced drilling such as maximizing hydrocarbon recovery and minimizing drilling problems.

In this work rock mechanics principals are used to elaborate a mathematical model to predict pressure drop required for safe underbalanced drilling. This model combine linear-poroelastic stress solution, Mohr-Coulomb failure criteria and rock mechanical properties. It compares the induced shear stresses with the experimental maximum allowable shear stress at failure for formation rock under consideration. Furthermore, the elaborated model can be used for vertical, directional or horizontal wells.

The model predicted that the allowable pressure drop required for safe underbalanced drilling is function of rock strength. Higher underbalanced pressure drop can be achieved for strong formations. On the other hand it is impossible to perform underbalanced drilling for unconsolidated or very weak or heavily fractured formations. Furthermore, higher underbalanced pressure drop can be performed for vertical wells if compared to horizontal-wells. Horizontal wells drilled parallel to the minimum horizontal in-situ principal stress are the most stable when drilled using underbalanced drilling technique.

Therefore, the mathematical model presented in this paper provides a powerful tool for prediction of the underbalanced pressure drop margin required when drilling vertical, directional or horizontal oil or gas wells.

2. Introduction

Underbalanced drilling is widely used nowadays to drill different types of reservoirs around the world. Figure 1 shows the expected annual growth of underbalanced drilling within the next five years [1]. Underbalanced drilling is defined as drilling with the hydrostatic pressure of the drilling fluid intentionally designed to be lower than the pore fluid pressure of the formation being drilled. The hydrostatic mud pressure may be naturally less than the formation pore fluid pressure or it can be induced. The induced state may be created by adding natural gas, nitrogen or air to the drilling mud. Whether the underbalanced status is induced or natural, the result will be an influx of formation fluids, which must be circulated from the well and controlled at surface [2]. The lower hydrostatic pressure avoids the build up of mud cake on the formation as well as invasion of the mud solids into the formation, which helps in improving the productivity of the reservoir. Thus the objectives of the underbalanced drilling are [2-7]:

(i) Maximizing hydrocarbon recovery by reducing formation damage, reducing stimulation jobs and extending the life of the reservoir.

(ii) Reducing rig and mud expenses by minimizing drilling problems such as reducing mud losses, avoiding pipe differential sticking and improving penetration rate.

(iii) Obtaining additional reservoir information during drilling from the flowing reservoir fluids.

The objective of this work is to develop a mathematical technique to simplify the selection process of pressure drop required for safe underbalanced drilling. The proposed technique accounts for formation mechanical properties, well geometry and reservoir fluid pressure.

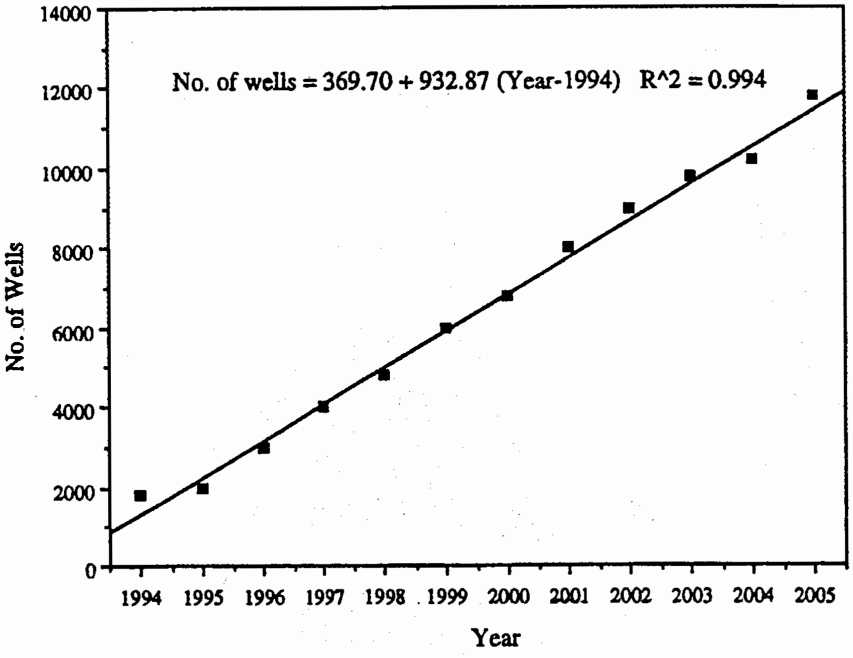

Fig. 1 Expected average annual growth of underbalanced drilling applications around the world [1].

3. The Mathematical Model

Rock mechanics principles are used to solve many problems facing the oil industry such as sand production, wellbore instability, hydraulic fracturing, etc [8]. In this work a mathematical model based on rock mechanics principals is elaborated to predict the pressure drop required for safe underbalanced drilling processes. This model combines in-situ principal stresses, well inclination, well orientation, formation strength criteria and formation physical properties. Formation rock failure criteria are evaluated using Mohr-Coulomb failure criteria which is one of the most famous and applied rock failure criterion. This criteria is defined as follows [9] :

$$\tau_f = \tau_o + \sigma \tan \phi \qquad ...(1)$$

Three mutual in-situ stresses are assumed namely, the vertical principal in-situ stress (σ_v), the maximum horizontal principal in-situ stress (σ_H) and the minimum horizontal principal in-situ stress (σ_h). Wellbore instability can be predicted when these principal in-situ stresses are transformed parallel to the wellbore axis (for inclined or horizontal wells) using the following matrices (see Fig. 2) [9, 10]:

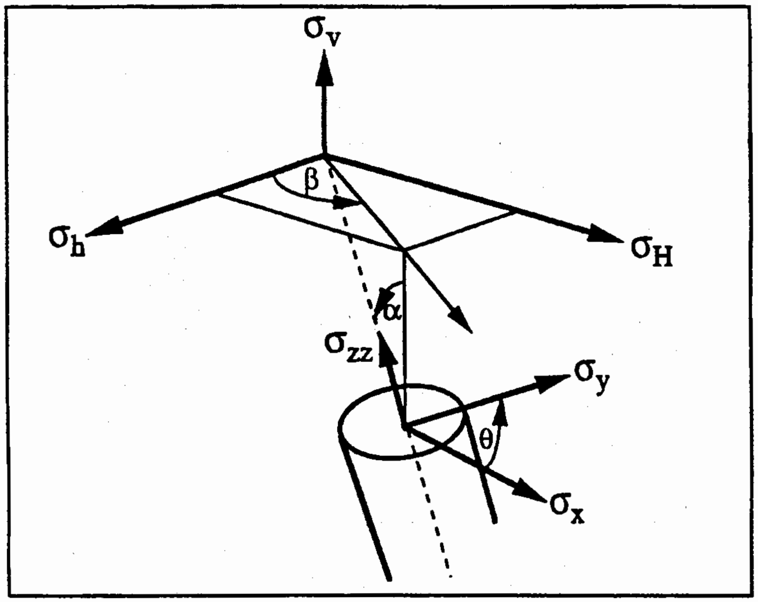

Fig. 2 Distribution of stresses acting on a deviated well.

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_{zz}\end{bmatrix} = \begin{bmatrix}\cos^2\beta\cos^2\alpha & \sin^2\beta\cos^2\alpha & \sin^2\alpha\\ \sin^2\beta & \cos^2\beta & 0\\ \cos^2\beta\sin^2\alpha & \sin^2\beta\sin^2\alpha & \cos^2\alpha\end{bmatrix}\begin{bmatrix}\sigma_H\\ \sigma_h\\ \sigma_v\end{bmatrix} \qquad ...(2)$$

$$\begin{bmatrix}\tau_{yz}\\ \tau_{xz}\\ \tau_{xy}\end{bmatrix} = \frac{1}{2}\begin{bmatrix}\sin 2\beta\sin\alpha & -\sin 2\beta\sin\alpha & 0\\ \sin 2\alpha\cos\beta & \sin^2\beta\sin 2\alpha & -\sin 2\alpha\\ \cos^2\beta\sin^2\alpha & -\sin 2\beta\cos\alpha & 0\end{bmatrix}\begin{bmatrix}\sigma_H\\ \sigma_h\\ \sigma_v\end{bmatrix} \qquad ...(3)$$

Three induced stresses are acting on the wall of a borehole. These are, the vertical induced stress (σ_z), the radial induced stress (σ_r) and the tangential induced stress (σ_θ) which can be computed as follows:

$$\begin{aligned}\sigma_r &= P_{wc}\\ \sigma_\theta &= (\sigma_x + \sigma_y - P_{wc}) - 2(\sigma_x - \sigma_y)\cos 2\theta - 4\tau_{xy}\sin 2\theta\\ \sigma_z &= \sigma_{zz} - 2v(\sigma_x - \sigma_y)\cos 2\theta - 4v\tau_{xy}\sin 2\theta\\ \tau_{r\theta} &= \tau_{rz} = 0\\ \tau_{\theta z} &= 2[-\tau_{zx}\sin\theta + \tau_{yz}\cos\theta]\end{aligned} \qquad ...(4)$$

By knowing the magnitude of the wellbore (mud) pressure, the induced principal stresses acting on the wall of a borehole can be computed as follows :

$$\begin{aligned}\sigma_1 &= \sigma_\gamma = P_{wc}\\ \sigma_2 &= \frac{1}{2}\left(\sigma_\theta + \sigma_z\right) - \frac{1}{2}\sqrt{\left(\sigma_\theta - \sigma_z\right)^2 + 4\tau_{\theta z}}\\ \sigma_3 &= \frac{1}{2}\left(\sigma_\theta + \sigma_z\right) + \frac{1}{2}\sqrt{\left(\sigma_\theta - \sigma_z\right)^2 + 4\tau_{\theta z}}\end{aligned} \qquad \text{...(5)}$$

Finally, borehole instability using underbalanced drilling can be predicted by comparing the computed and the experimentally measured shear stresses (see Fig. 3) as follows [11, 12] :

$$\tau_{f_{Experimental}} = \tau_o + \left[\frac{\sigma_1 + \sigma_3}{2}\right]\tan\phi \qquad \text{...(6)}$$

$$\tau_{f_{Model}} = \left[\frac{\sigma_1 - \sigma_3}{2}\right] \qquad \text{...(7)}$$

Therefore, borehole instability will take place if the model predicted shear stress is equal or greater than the laboratory measured shear stress. Data shown in Table 1 are used to predict the safe pressure drop required for safe underbalanced drilling.

Vertical principal in-situ stress (σ_v) = 1.0 psi/ft.

Horizontal Maximum principal in-situ stress (σ_H) = 0.85 psi/ft.

Horizontal Minimum principal in-situ stress (σ_h) = 0.75 psi/ft.

Poisson's ratio (ν) = 0.22.

Angle of internal friction (ϕ) = 24 degrees.

Apparent cohesion (τ_o) = ranging from 160 psi to 1900 psi

Uniaxial compressive strength (σ_c) = ranging from493 psi to 5850 psi.

Pore fluid pressure (D) = 4000 psi.

Well true vertical depth = 7200 ft.

Inclination angle (α) 0° for vertical well and 90° for horizontal well.

Orientation angle (β) = 0° for well parallel to σ_H and 90° for well parallel to σ_h.

Rotation angle around the wellbore θ = 90°.

Table 1 Formation properties used as model input data.

Well configuration	Acting stresses	Ultimate differential stress value, psi
Vertical well parallel to the vertical in-situ principal stress (σ_v).	σ_H and σ_h	$0.85 - 0.75 = 0.10$
Horizontal well parallel to the minimum principal in-situ stress ((σ_h)).	σ_v and σ_H	$1.00 - 0.85 = 0.15$
Horizontal well parallel to the maximum principal in-situ stress (σ_H)	σ_v and σ_h	$1.00 - 0.75 = 0.25$

Table 2 Acting in-situ differential stress for various well configurations.

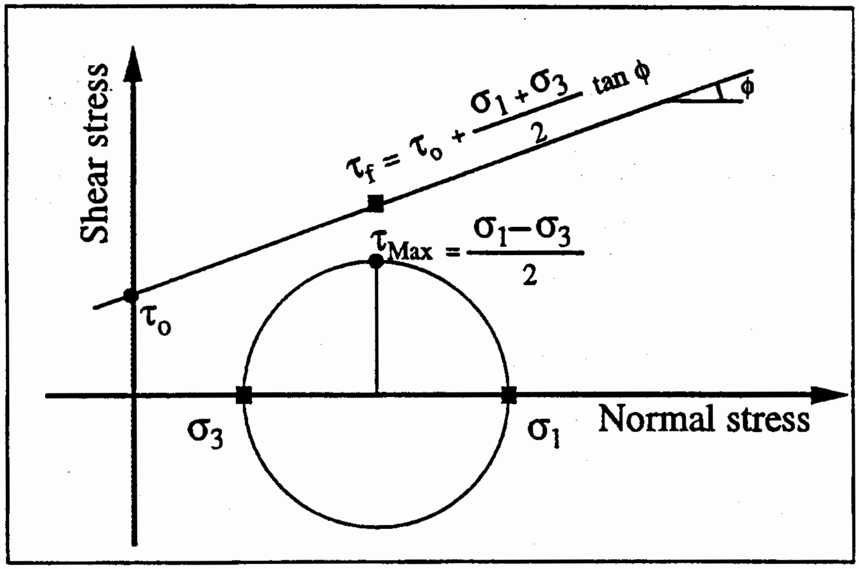

Fig. 3 Representation of shear stresses acting on the vicinity of a borehole

4. Results and Discussion

Successful application of the underbalanced drilling depends mainly on the monitoring and manipulating the hydrostatic pressure of the drilling fluid. By using the mathematical model described in this work, the range of the allowable pressure drop in underbalanced drilling was predicted to ensure hole stability while drilling. Figure 4 shows the range of allowable pressure drop for safe underbalanced drilling of three well configurations. In this figure, different compressive strength values were taken to calculate the allowable pressure drop. It shows that horizontal wells drilled parallel to the minimum in-situ principal stress (σ_h) have the widest range of allowable pressure drop that can be applied while borehole stability is maintained. In this case the two in-situ stresses that have an influence on borehole stability are the maximum horizontal principal in-situ (σ_H) and the vertical principal in-situ (σ_v) as shown in Table 2. Therefore, under the assumed in-situ stress state, safe underbalanced drilling operations can be performed only for formation having a compressive strength greater than 6000 psi. The other case of horizontal wells that drilled parallel to the maximum principal horizontal in-situ stress (σ_H), the minimum horizontal principal in-situ (σ_h) and the vertical principal in-situ (σ_v) are the acting stresses. Thus, the range of pressure drop required that for safe underbalanced drilling can be performed only if the target formation compressive strength exceeds 7600 psi approximately otherwise borehole instability (collapse) occurs.

In case of vertical well, the in-situ principal stress that influence the stability of the well are the minimum principal horizontal in-situ stress (σ_h), the maximum horizontal principal in-situ (σ_H). Therefore an underbalanced drilling can performed safely only for formations having a compressive strength greater than 4500 psi under the same in- situ stress state shown in Table 1. However, borehole instability occurs if an underbalanced drilling operation would be performed in formations with a compressive strength below 4500 psi regardless the direction or the type of the drilled hole.

Therefore the mathematical model presented in this paper can be applied for any type of reservoir to predict the underbalanced or overbalanced limit in order to maintain borehole stability while drilling.

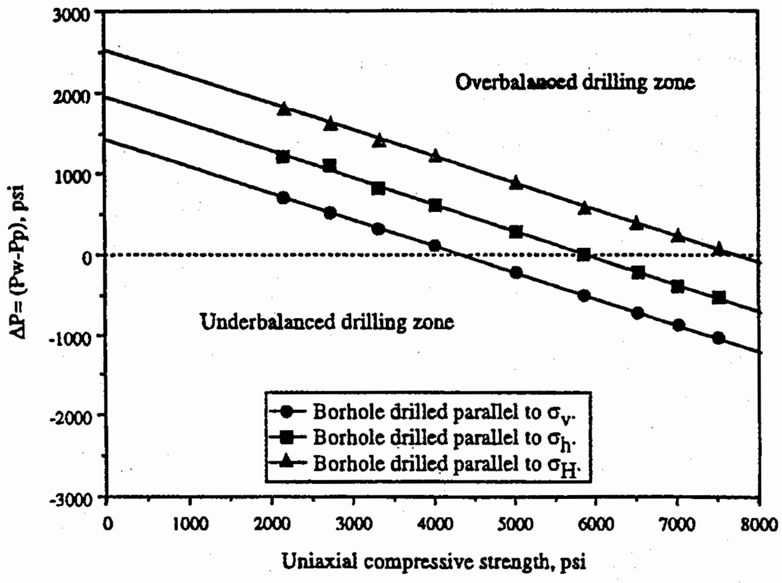

Fig. 4 Predicted allowable pressure drop required for safe underbalanced drilling operations.

5. Conclusions

Based on the output data gained from the application of the elaborated model presented in this paper, the following conclusions are obtained:

- Pressure drop required for safe underbalanced drilling is function of rock strength.
- In horizontal wells, the margin for underbalanced pressure drop was found less compared to vertical wells.
- Horizontal wells drilled parallel to the minimum horizontal in-situ principal stress are the most stable when drilled using underbalanced drilling technique.
- Borehole instability occurs if underbalanced drilling is performed for unconsolidated, weak or heavily fractured formations.

REFERENCES

1. Duda, J., Medley, G. and Deskins, G. : "Strong Growth Projected For Underbalanced Drilling.", Oil And Gas Journal, (Sept. 1996).
2. "Underbalanced Drilling Technology.", By Deutag Northland Underbalanced Drilling Services, Presented At The Proceedings Of The 1999 SPE Technical Symposium, Dhahran, Saudi Arabia, (25-27 October, 1999).
3. Butler, S. D. and Teichrob, R., R. : "Monitoring Downhole Pressures And Flow Rates Critical For Underbalanced Drilling.", Oil and Gas Journal, (Sept. 16 1996) 31-39.
4. Bennoin, D. B., Thomas, F. B., Bietz, R. F. and Bennoin, D. W. : "Underbalanced Drilling: Praises and Perils.", SPE Drilling & Completion, (December, 1998).
5. Koji Kusaka, Dinesh Patel, Sam Gomersall, John Mason and Phil Doughty: "Underbalance Perforation In Long Horizontal Wells In He Andrew Field.", SPE Drilling & Completion, (December, 1998).
6. Adam, T. and Bourgoynr, Jr. : "Well Control Considerations For Underbalanced Drilling.", SPE Paper No. 38584 Presented At The 1997 SPE Annual Technical Conference, San Antonio, Texas, (5-8 October, 1997).
7. Bennion, D. B., Thomas, F. B., Jamaluddin, A. K. M. and Ma, T. : "Using Underbalanced Drilling To Reduce Invasive Formation Damage And Improve Well Productivity.", Journal Of Canadian Petroleum Technology, Vol. 39, No. 7, (2000) 52-60.
8. Musaed N. J. Al-Awad : "Rock Mechanics Applications In Petroleum Engineering Practices.", Oil And Gas European Magazine, Germany, (December 1998) 18-20.
9. Fjaer E., Holt R. M., Horsrud P., Raaen A.R. and Risnes R. : "Petroleum Related Rock Mechanics.", Eisevier Science Publishers B.V., Amsterdam, The Netherlands, 1st edition, (1992) 338.

10. Musaed N. J. Al-Awad : "Investigation Of Factors Affecting The Stability Of Horizontal Oil And Gas Wells.", 1997 SPE Technical Symposium, Saudi Aramco, Dhahran, (June 8-10, 1997) 79-90.

11. Musaed N. J. Al-Awad : "The Investigation Of The Source Of Sand Produced Ftom Competent Sandstone Reservoirs.", The Second Jordanian Mining Conference, Jordanian University, Amman, Jordan, (April 26-29, 1997) 393-405.

12. Musaed N. J. Al-Awad, and Saad El-Din M. Desouky : "Prediction Of Sand Production From A Saudi Sandstone Reservoir.", Revue De L' Institute Francias Du Petrole, Vol. 52, No. 4, (July-August, 1997) 1-8.