空间圆弧轨道的描述与计算

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摘　要　空间圆弧作为一种典型的井眼轨道模型,广泛应用于多目标井、分支井、侧钻井等三维井眼轨道设计,以及定向井、水平井和大位移井的调整轨道设计。由于三维井眼轨道的设计与计算通常都是在垂直剖面图和水平投影图上进行的,而空间圆弧在这两个平面上又都不是像圆弧那样的简单的曲线形式,所以增加了问题的复杂性。由于这种原因,目前对空间圆弧轨道的计算多采用近似公式。文章结合井眼轨道的设计要求和空间圆弧的特点,提出了空间圆弧轨道上的坐标、井斜角、方位角、井斜变化率、方位变化率和装置角的计算公式。这些计算公式在理论上是精确解,具有普遍适用性,从而为空间圆弧轨道模型的进一步应用和三维井眼轨道设计奠定了基础。所有公式都通过算例进行了验证。

主题词　钻井理论　定向井　水平井　轨道设计　数学模型　井眼轨迹

理 论 研 究

通常,空间圆弧是三维井眼轨道的一个组件。在进行井眼轨道设计时,由于设计目的和设计条件不同,因此已知条件和所需求解的参数也存在一定的差异。本文的计算公式将以如下参数作为已知条件:①起始点的井斜角(α_1)和方位角(ϕ_1);②起始点的坐标(X_1, Y_1, Z_1)及水平位移(S_1);③造斜率(K);④初始装置角(ω)(以下简称装置角)。

在进行空间圆弧轨道的设计与计算时,上述参数一般都作为已知条件给出。即使有的参数是未知的,利用一些基本关系式,也是不难求得的。

1. 空间坐标

首先,建立整体坐标系 $O-XYZ$ 和局部坐标系 $1-\xi\eta\zeta$。整体坐标系的 X 轴和 Y 轴分别指向北、东方向,Z 轴铅垂向下指向地心。通常,坐标原点 O 选在井口,当然也可以选在其它位置上。局部坐标系的原点选在圆弧段的起始点上,ξ 轴指向轨道的前进方向,η 轴在斜平面内垂直于 ξ 轴且指向圆弧段的结束点一侧,ζ 轴为斜平面 Ω 的法线方向。可见,它们均为右手坐标系。如图 1 所示。

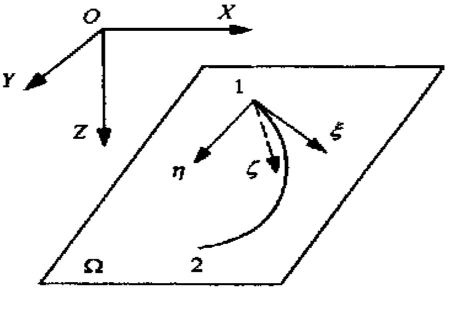

图 1　空间圆弧及坐标系示意图

根据几何关系,可以建立整体坐标系和局部坐标系之间的转换关系。由于空间圆弧位于某个斜平面 Ω 内,且过圆弧段的起始点及其切线,所以如果给定该圆弧段的装置角(ω),则坐标转换关系可表示为[1]:

$$\{X - X_1, Y - Y_1, Z - Z_1\}^T = [T]\{\xi, \eta, \zeta\}^T \quad (1)$$

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其中

$$\begin{cases} T_{11} = \sin\alpha_1\cos\phi_1 \\ T_{12} = \cos\alpha_1\cos\phi_1\cos\omega - \sin\phi_1\sin\omega \\ T_{13} = -\cos\alpha_1\cos\phi_1\sin\omega - \sin\phi_1\cos\omega \\ T_{21} = \sin\alpha_1\sin\phi_1 \\ T_{22} = \cos\alpha_1\sin\phi_1\cos\omega + \cos\phi_1\sin\omega \\ T_{23} = -\cos\alpha_1\sin\phi_1\sin\omega + \cos\phi_1\cos\omega \\ T_{31} = \cos\alpha_1 \\ T_{32} = -\sin\alpha_1\cos\omega \\ T_{33} = \sin\alpha_1\sin\omega \end{cases}$$

通过坐标变换,就把空间问题转化成了平面问题,如图2所示。

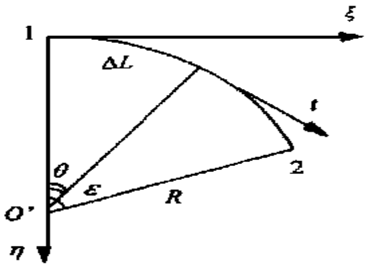

图2　斜平面上的圆弧轨道

在局部坐标系 1—ξηζ 中,不难得出:

$$\begin{cases} \xi = R\sin\theta \\ \eta = R(1-\cos\theta) \\ \zeta = 0 \end{cases} \qquad (2)$$

其中

$$R = \frac{180\,C_K}{\pi K} \qquad \theta = \frac{180}{\pi}\cdot\frac{L-L_1}{R} = \frac{K(L-L_1)}{C_K}$$

当造斜率(K)的单位分别为°/10m、°/25m、°/30m、°/100m时,单位换算系数(C_K)的取值分别为10、25、30和100。

这样,便可以计算出空间圆弧轨道上任意井深 L 处的空间坐标(X,Y,Z)。

2. 井斜角和方位角

井斜角和方位角反映了井眼轨道切线的方向。在局部坐标系下,空间圆弧轨道上单位切线矢量(t)可表示为:

$$t = \cos\theta e_\xi + \sin\theta e_\eta \qquad (3)$$

而由单位矢量的坐标变换[2],知

$$\begin{cases} e_\xi = \dfrac{\frac{\partial\xi}{\partial X}i + \frac{\partial\xi}{\partial Y}j + \frac{\partial\xi}{\partial Z}k}{\sqrt{\left(\frac{\partial\xi}{\partial X}\right)^2 + \left(\frac{\partial\xi}{\partial Y}\right)^2 + \left(\frac{\partial\xi}{\partial Z}\right)^2}} \\ e_\eta = \dfrac{\frac{\partial\eta}{\partial X}i + \frac{\partial\eta}{\partial Y}j + \frac{\partial\eta}{\partial Z}k}{\sqrt{\left(\frac{\partial\eta}{\partial X}\right)^2 + \left(\frac{\partial\eta}{\partial Y}\right)^2 + \left(\frac{\partial\eta}{\partial Z}\right)^2}} \end{cases} \qquad (4)$$

所以,t 在整体坐标系下的表达形式为:

$$t = (T_{11}\cos\theta + T_{12}\sin\theta)i + (T_{21}\cos\theta + T_{22}\sin\theta)j + (T_{31}\cos\theta + T_{32}\sin\theta)k \qquad (5)$$

进而,可以得出任意井深下的井斜角和方位角:

$$\cos\alpha = T_{31}\cos\theta + T_{32}\sin\theta \qquad (6)$$

$$\mathrm{tg}\phi = \frac{T_{21} + T_{22}\mathrm{tg}\theta}{T_{11} + T_{12}\mathrm{tg}\theta} \qquad (7)$$

3. 井斜变化率和方位变化率

井斜变化率和方位变化率是空间圆弧轨道计算的又一个难点,这是因为空间圆弧在井斜平面和方位平面内都不是简单的曲线形式。所以,目前对它们的研究几乎是空白。

根据井斜变化率(K_α)和方位变化率(K_ϕ)的定义以及式(6)和式(7),得:

$$K_\alpha = \frac{K}{\sin\alpha}(T_{31}\sin\theta - T_{32}\cos\theta) \qquad (8)$$

$$K_\phi = K\left(\frac{\cos\phi}{\cos\theta}\right)^2 \frac{T_{22} - T_{12}\mathrm{tg}\phi}{T_{11} + T_{12}\mathrm{tg}\theta} \qquad (9)$$

可以验证,它们满足关系式:

$$K = \sqrt{K_\alpha^2 + K_\phi^2\sin^2\alpha} \qquad (10)$$

4. 装置角

尽管目前已有两个空间圆弧井段装置角的计算公式[1],但在井眼轨道设计与计算中使用不便。本文提出的装置角计算公式,具有形式简单、使用方便等特点,可以根据空间圆弧起始点和结束点的井斜角和方位角直接计算出装置角。

对于空间圆弧轨道,存在如下关系式[1]:

$$\sin\omega = \frac{\sin\alpha_2\sin(\phi_2 - \phi_1)}{\sin\varepsilon} \qquad (11)$$

$$\sin\alpha_2 = \frac{\sin\alpha_1\cos\varepsilon + \cos\alpha_1\sin\varepsilon\cos\omega}{\cos(\phi_2 - \phi_1)} \qquad (12)$$

$$\cos\varepsilon = \cos\alpha_1\cos\alpha_2 + \sin\alpha_1\sin\alpha_2\cos(\phi_2 - \phi_1) \qquad (13)$$

式中:α_2、ϕ_2、ε 分别为圆弧段结束点的井斜角、方位角以及圆弧段的弯曲角。

联立式(11)～(13),经整理可得:

$$\mathrm{tg}\omega = \frac{\sin(\phi_2 - \phi_1)}{\cos\alpha_1\left[\cos(\phi_2 - \phi_1) - \dfrac{\mathrm{tg}\alpha_1}{\mathrm{tg}\alpha_2}\right]} \qquad (14)$$

算 例 验 证

某水平井钻至井深 1 370 m 时，井斜角 $\alpha_1 = 42°$，方位角 $\phi_1 = 135°$。如果工具的造斜能力 $K = 8°/30\mathrm{m}$，要求当井斜角 $\alpha_2 = 50°$ 时，方位角 $\phi_2 = 120°$，试设计该调整轨道。

(1) 计算曲率半径和装置角

$$R = \frac{180 \times 30}{\pi \times 8} = 214.86\ \mathrm{m}$$

$$\omega = \mathrm{tg}^{-1}\left\{\frac{\sin(120° - 135°)}{\cos42°\left[\cos(120° - 135°) - \dfrac{\mathrm{tg}42°}{\mathrm{tg}50°}\right]}\right\}$$

$$= 301.14°$$

然后，便可利用本文的方法，逐点计算出该空间圆弧轨道上的参数。下面以圆弧段的结束点为例给出计算步骤。

(2) 求坐标转换矩阵

$T_{11} = \sin42° \cos135° = -0.473\ 15$

$T_{12} = \cos42° \cos135° \cos301.14° - \sin135° \sin301.14° = 0.333\ 47$

$T_{13} = -\cos42° \cos135° \sin301.14° - \sin135° \cos301.14° = -0.815\ 43$

$T_{21} = \sin42° \sin135° = 0.473\ 15$

$T_{22} = \cos42° \sin135° \cos301.14° + \cos135° \sin301.14° = 0.876\ 96$

$T_{23} = -\cos42° \sin135° \sin301.14° + \cos135° \cos301.14° = 0.084\ 10$

$T_{31} = \cos42° = 0.743\ 15$

$T_{32} = -\sin42° \cos301.14° = -0.346\ 03$

$T_{33} = \sin42° \sin301.14° = -0.572\ 71$

(3) 圆弧段的弯曲角

$$\varepsilon = \cos^{-1}[\cos42° \cos50° + \sin42° \sin50° \cos(120° - 135°)] = 13.39°$$

(4) 圆弧段的段长

$$\Delta L = \frac{30 \times 13.39}{8} = 50.21\ \mathrm{m}$$

(5) 圆弧段结束点在局部坐标系下的坐标

$$\begin{cases} \xi_2 = 214.86\sin13.39° = 49.76\ \mathrm{m} \\ \eta_2 = 214.86 \times (1 - \cos13.39°) = 5.84\ \mathrm{m} \\ \zeta_2 = 0 \end{cases}$$

(6) 圆弧段的坐标增量

$$\begin{cases} \Delta X = -0.473\ 15 \times 49.76 + 0.333\ 47 \times 5.84 \\ \quad = -21.59\ \mathrm{m} \\ \Delta Y = 0.473\ 15 \times 49.76 + 0.876\ 96 \times 5.84 \\ \quad = 28.66\ \mathrm{m} \\ \Delta Z = 0.743\ 15 \times 49.76 - 0.346\ 03 \times 5.84 \\ \quad = 34.96\ \mathrm{m} \end{cases}$$

(7) 圆弧段结束点的井斜角和方位角

$$\alpha_2 = \cos^{-1}(\cos42° \cos13.39° - \sin42° \cos301.14° \sin13.39°) = 50.00°$$

$$\phi_2 = \mathrm{tg}^{-1}\left[\frac{\sin42° \sin135° + (\cos42° \sin135° \cos301.14° + \cos135° \sin301.14°)\mathrm{tg}13.39°}{\sin42° \cos135° + (\cos42° \cos135° \cos301.14° - \sin135° \sin301.14°)\mathrm{tg}13.39°}\right]$$

$$= \mathrm{tg}^{-1}\left(\frac{0.681\ 907}{-0.393\ 764}\right) = 120.00°$$

(8) 圆弧段结束点的井斜变化率和方位变化率

$$K_\alpha = \frac{8}{\sin50°}(0.743\ 15\sin13.39° + 0.346\ 03\cos13.39°) = 5.31°/30\mathrm{m}$$

$$K_\phi = 8 \times \left(\frac{\cos120°}{\cos13.39°}\right)^2 \frac{0.876\ 96 - 0.333\ 47\mathrm{tg}120°}{-0.473\ 15 + 0.333\ 47\mathrm{tg}13.39°} = -7.81°/30\mathrm{m}$$

由于

$$K = \sqrt{5.31^2 + (-7.81)^2\sin^2 50°} = 8.00°/30\mathrm{m}$$

所以，井斜变化率和方位变化率的计算结果是正确的。其它参数的计算结果可以通过最小曲率法得到验证[1]。该调整轨道的设计结果，见表 1。

表 1　调整轨道的设计与计算结果

段长 (m)	井斜角 (°)	方位角 (°)	北坐标增量 (m)	东坐标增量 (m)	垂深增量 (m)	井斜变化率 (°/30m)	方位变化率 (°/30m)
0.00	42.00	135.00	0.00	0.00	0.00	4.14	-10.23
10.00	43.43	131.68	-4.65	4.93	7.35	4.42	-9.70
20.00	44.95	128.53	-9.14	10.26	14.52	4.68	-9.18
30.00	46.55	125.56	-13.45	15.98	21.50	4.92	-8.69
40.00	48.22	122.73	-17.58	22.07	28.27	5.12	-8.24
50.00	49.96	120.06	-21.51	28.52	34.82	5.31	-7.82
50.21	50.00	120.00	-21.59	28.66	34.96	5.31	-7.81

结　　论

(1) 本文对空间圆弧轨道的描述与计算进行了较为系统的研究，所得出的计算公式均为精确解，具有普遍适用性。

(2) 本文的研究内容可广泛应用于多目标井、分支井和侧钻井的设计，以及定向井、水平井和大位移井的调整轨道设计。

气藏泡沫欠平衡钻井数学模型研究

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罗世应等. 气藏泡沫欠平衡钻井数学模型研究. 天然气工业 ,2000 ;20(5) :47～50

摘　要　文章首先指出泡沫具有低失水、低伤害 ,在井下和地层产出天然气混合后不易发生爆炸的特点 ,因此气藏泡沫欠平衡钻井技术安全可靠、保护储层效果好 ,其具有广泛的应用前景。然后 ,利用质量守恒与动量守恒方程以及流变方程建立了泡沫流经钻柱内、钻头、环空不同位置的数学模型 ,采用数值迭代方法对数学模型进行了求解。最后给出了计算实例 ,并在实例的计算结果中讨论了地层产出气体、注入气量、回压等对井内流动参数与地面施工参数的影响规律。得到了回压的增加 ,井底压力不总是升高 ,而回压的降低 ,地层产出气速度也不总增加等结论。本文建立的模型可以用于泡沫欠平衡钻井修井理论设计、施工参数优化。

主题词　气藏　泡沫　欠平衡钻井　数学模型

泡沫是一种分散的均匀流体 ,自身独特的结构特点决定了泡沫流体具有许多优点 ,如 :低滤失 ,对储层伤害小以及强携岩携水等性能。目前 ,泡沫流体在石油工业的钻井、完井、采油以及压裂酸化等领域都显示出很大的应用潜力。尤其欠平衡钻井时 ,采用泡沫流体打开气层 ,更是理想的选择。这是因为 :一方面 ,气藏原始含水饱和度往往低于其束缚水饱和度 ,当用水基钻井液打开气藏时 ,在毛细管压力的作用下 ,钻井液中的水容易渗吸到地层 ,形成水锁或液相圈闭 ,造成储层伤害。所以 ,气层的特点是“怕”水。泡沫流体的自由水含量很低 ,加之泡沫对地层的孔隙或裂缝具有封堵作用 ,其侵入地层的水是极少的。另一方面 ,欠平衡钻井时 ,地层不断地产出气 ,在井内是否会爆炸 ,值得认真考虑。泡沫流体在钻气藏时 ,不用担心井内燃烧爆炸 ,这是由泡沫自身的结构特点决定的。基于这种认识 ,作者相信泡沫在气藏欠平衡钻井中会得到广泛的应用。因此 ,了解泡沫在井内的流动规律 ,建立正确合理的泡沫欠平衡钻井数学模型是十分必要的。

泡沫欠平衡钻井的物理模型

如图 1 所示 ,欠平衡钻井时 ,泡沫钻井液由钻柱井口注入 ,流经钻柱 ,钻头 ,在井底携带钻头破碎的岩屑与地层产出流体后 ,由环空返出地面。泡沫在井内属多相流动 ,要精确描述其流动特征 ,计算井内的流动参数 ,优化钻井作业 ,问题既复杂 ,但又必需。

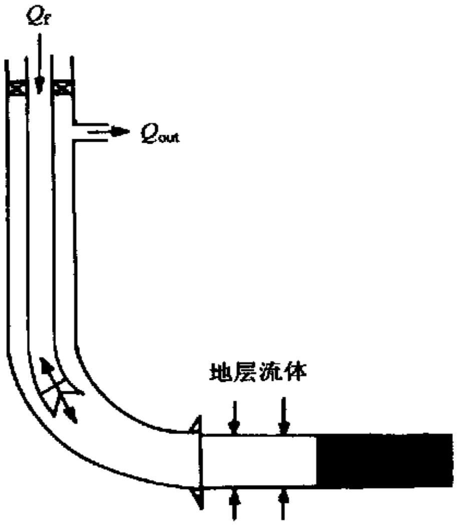

图 1　欠平衡钻井物理模型示意图

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SEISMIC RESPONSE CHARACTERISTICS OF SHALLOW GAS IN THE CENTRE-SOUTH PART OF WEST SICHUAN DEPRESSION

Yang Kaizhen, Chen weiming and Li Shushun (Geological Research Institute of Southwest Petroleum Bureau). *NATUR. GAS IND*. v. 20, no. 5, pp. 39～41, 9/25/2000. (ISSN 1000 - 0976; **In Chinese)**

ABSTRACT: In recent years, the shallow natural gas exploration and development in Sichuan Basin have entered into a new stage and its reserves and production are rapidly increased, which plays an important role in these respects as evaluation exploration, detailed 2-D and 3-D seismic interpretation, detailed reservoir description, reserve estimation and making up development plan, etc. In light of the practice of the shallow natural gas exploration and development and the detailed processing and interpretation of seismic data, it is shown that the geophysical response characteristics of shallow gas-bearing sandbodies are the major bases of interpreting and calibrating gas-bearing sandbodies. The method of differentiating the gas potential of the sandbodies may be determined by use of multivariable comprehensive analysis technique on the basis of a change in its amplitude. In this region, while the wave impedance of gas-bearing sandbody is smaller than its up-and-down sourrounding rocks, the reflection of its top-and-bottom interfaces shows the characteristics as a negative at top and a positive at bottom, relatively low (apparent) frequency and relatively strong amplitude, i. e, the larger the wave impedance difference between the gas-bearing sandbody and its overlying formation, the stronger the amplitude of reflection wave trough; the larger the wave impedance difference between the gas-bearing sandbody and its underlying bed, the stronger the amplitude of reflection wave crest.

SUBJECT HEADINGS: Sichuan Basin, West, Shallow gas, Seismic data processing, Seismic interpretation, Sand body, Lateral prediction

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EMULATION OF THE STRUCTURE OF DQ-30Y DRILLING-WORKOVER DUAL-PURPOSE TOP DRIVE DEVICE

Xiao Xiaohua and Liu Qingyou (Mechanical Department of Southwest Petroleum Institute) and Xie Bin (Research Institute of Oil Production Technology, Xinjiang Petroleum Administration). *NATUR. GAS IND*. v. 20, no. 5, pp. 42～43, 9/25/2000. (ISSN 1000 - 0976; **In Chinese)**

ABSTRACT: The research works on the structural characters, working mechanism and structure emulation of a drilling-workover dual-purpose top drive device which is driven by full-hydraulic way and can satisfy the operations in slim-hole drilling, directional drilling, side-tracking and well workover, etc. is presented in this paper. The emulation research on the structure of DQ-30Y drilling-workover dual-purpose top drive device has been realized by adopting the automatic design software (Pro/engineer) in the process of developing this device and through setting up the 3-D solid model of each parts and component, the structure assemblage, the interference inspection and the mechanics analysis. The existent problems in the design and assemblage of this device's parts and component have been found out, the design proposal has been promptly altered and the found problems and the proposals for modification have been informed to the developmental unit, shortening, thus, the development cycle of this product, reducing the development cost and raising the realiability of this product and its competitive power in the market.

SUBJECT HEADINGS: DQ-30Y, Drilling, Workover rig, Top drive drilling, Simulation

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DESCRIPTION AND CALCULATION OF THE WELL PATH WITH SPATIAL ARC MODEL

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ABSTRACT: Spatial arc , as a typical model to plan a 3D well path ,is widely applied in planning the path of multiple targets well ,branch well ,sidetrack well and in rectifying the path of directional well , horizontal well and extended-reach well. The problem becomes even more complicated for two reasons : A 3D well path is usually planned and calculated in the vertical plot and the horizontal plot ;on the other hand the spatial arc is not a simple curve as arcs in these two plots. As a result ,approximation formulae have been used to calculate a spatial arc. According to the plan demand of well path and the feature of spatial arc ,a series of formulae ,including coordinate ,inclination ,azimuth ,rate of inclination change ,rate of azimuth change and tool face angle ,are presented in this paper for spatial arc model. All of these formulae ,testified by many examples ,provided such exact solutions abstractly that they lay a foundation for the further application of spatial arc model and the path plan improvement of 3D wells.

SUBJECT HEADINGS : Drilling theory , Directional well , Horizontal well ,Mathematical model ,Hole trajectory

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A STUDY OF MATHEMATICAL MODEL OF FOAM UNDERBALANCED DRILLING IN GAS RESERVOIR

Luo Shiying ,Meng Yingfeng and Li Yun (Southwest Petroleum Institute) and Zhao Bin (Henan Oil Field) . *NATUR. GAS IND.* v. 20 ,no. 5 ,pp. 47～50 , 9/ 25/ 2000. (ISSN 1000 - 0976 ; **In Chinese)**

ABSTRACT : The paper first indicates that foam has low filtration and low damage to formation and explosion is not easy to happen when it is mixed with the natural gas from reservoir in well ,which shows that the foam underbalanced drilling technique for gas reservoir is safe and reliable ,has a good effect in reservoir protection and is of a broad prospects for its application. Then , the mathematical models of foam flowing through different positions (drilling string ,bit and annulus) are set up based on the mass conservative equation , momentum conservative equation and rheological equation and an iterative method is used to solve for the mathematical model. Finally ,a calculation example is given out and the law of the influence of the gas produced from reservoir ,the injected gas rate and the back pressure on the foam flow parameters in the well and on the surface operation parameters is discussed in the calculation result of the example ,concluding that the bottom pressure does not always increase with the increase in the back pressure and the rate of the gas produced from reservoir does not always increase with the decrease in the back pressure. The models developed in this paper can be used for the theoretical design of foam underbalanced drilling and workover and for the optimization of the operation parameters.

SUBJECT HEADINGS : Gas pool , Foam , Underbalanced drilling ,Mathematical model

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DETERMINATION OF THE ACID VOLUME IN ACIDIZING AND FRACTURING OPERATIONS BY EXPERIMENTIZING DYNAMIC FILTER LOSS OF ACIDIZING FLUID

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ABSTRACT : The effective action radius of acidizing fluid is mainly controlled by its filter loss for the low-permeability carbonate reservoirs with relatively developed microfractures and serious fluid loss. However ,the filter loss of acidizing fluid is much complex as compared with the fracturing fluid due to its specific reaction property ,and a perfect model of the filter loss of acidizing fluid is not set up yet to this day ,making the acid volume difficult to determine scientifically in drawing up an operation plan. In this paper ,an experimental method for the dynamic filter loss of acidizing fluid is presented ,the characteristics of the filter loss