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四川盆地灯影组酸压裂缝导流能力实验和模拟研究

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摘要：酸压是深层、超深层海相碳酸盐岩油气藏增产的核心技术，而如何在超高温和高闭合应力下保持住酸蚀裂缝导流能力是酸压改造能否成功的关键。利用自研的高温高压酸蚀裂缝导流能力测试装置开展不同酸液及组合下灯影组岩样裂缝导流能力实验，使用三维激光扫描仪获取酸刻蚀裂缝形貌，基于此，采用Airy（艾里）应力函数和复变量法，描述酸蚀裂缝闭合程度，结合局部立方定律，耦合酸压模型，形成了酸蚀裂缝导流能力数值计算方法。结果表明：与低闭合应力（5 MPa）相比，高闭合应力（90 MPa）下多数酸液及其组合的导流能力降低了一个数量级；闭合应力增加，不同酸液及组合的导流能力降低模式有较大区别，可能会出现2次快速下降阶段；不同酸液组合注入可在一定程度上改善超高温和高闭合应力下酸蚀裂缝导流能力；酸蚀裂缝导流能力计算模型与实验结果平均误差较小，约10.6%，且能表征缝内各处导流能力分布及大小；相同工程参数条件下，四川盆地灯影组四段酸压裂缝导流能力较灯影组二段更高，可为四川盆地深层、超深层海相碳酸盐岩酸压改造方案优化设计提供理论指导。

关键词：碳酸盐岩；酸压；导流能力；酸液组合；数值模拟
中图分类号：TE357 **文献标识码**：A

Experimental and simulation study on fracture conductivity of acid-fracturing in Dengying Formation of Sichuan Basin

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Abstract: Acid fracturing is a critical stimulation technology for enhancing production in ultra-deep marine carbonate reservoirs. A significant challenge in this process is maintaining the conductivity of acid-etched fractures under ultra-high temperature and high closure stress conditions. To address this, conductivity experiments were conducted using various acid solutions and their combinations. The morphology of the acid-etched fractures was captured using a three-dimensional laser scanner. The degree of fracture closure was analyzed using the Airy stress function and the complex variable method, integrated with the local cubic law and an acid fracturing model to create a numerical calculation method for evaluating the conductivity of acid-etched fractures. The results show that under high closure stress (90 MPa), the conductivity of acids and their combinations decreases by an order of magnitude compared to low closure stress (5 MPa). As closure stress increases, different acids and combinations exhibit distinct patterns of conductivity reduction, with potential for two rapid decline phases. Furthermore, specific acid combinations have been identified that enhance the conductivity of fractures under extreme conditions of temperature and pressure. The average error between the conductivity values calculated by the model and those obtained from experimental results is relatively low, about 10.6%, indicating that the model can effectively characterize the distribution and magnitude of conductivity across different points within the fracture. In Sichuan Basin, under identical engineering parameters, the conductivity of acid-etched fractures in the 4th member of Dengying Formation is higher than that in the 2nd member. This research provides valuable theoretical guidance for optimizing the design of acid fracturing stimulation schemes in ultra-deep marine carbonate rocks in Sichuan Basin.
Keywords: carbonate; acid-fracturing; conductivity; acid combination; numerical simulation

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据不完全统计[1-6],碳酸盐岩油气储量约占全球油气总储量的56%,碳酸盐岩油气产量约占全球油气总产量的60%,而海相碳酸盐岩可采储量达2 376.5×10^8 t油当量,其开发前景广阔。四川盆地(安岳、高石梯、磨溪、射洪—盐亭等)、塔里木盆地(塔河、顺北、塔北、塔中等)、鄂尔多斯盆地西缘等在海相碳酸盐岩储层均有重大油气发现。因此,中国石油和中国石化将海相碳酸盐岩纳入“十四五”期间重点勘探开发范畴[7-9]。酸压是深层、超深层海相碳酸盐岩储层增产改造的核心技术之一,而酸蚀裂缝有效长度和酸蚀裂缝导流能力是酸压技术研究的2个核心内容[10-14]。四川盆地海相碳酸盐岩储层埋深已达6 000～7 000 m,部分已达8 260～8 950 m,如蓬深6井灯影组二段(以下简称灯二段)。深层、超深层给储层酸压改造带来了系列问题和挑战。例如,高温加剧酸液腐蚀和加快酸-岩反应速率、高闭合应力致使酸蚀裂缝闭合和低导流能力、高储层破裂压力和井筒摩阻致使难以压开储层等。

以酸蚀裂缝导流能力为研究对象,国内外诸多学者开展了大量实验和理论模型研究,并取得了一系列重要认识。赵立强等[15]、ZHANG等[16]、AL-MOMIN等[17]、牟建业等[18]、李小刚等[19]、ALJAWAD等[20]、苟申延等[21]、李沁等[22]使用酸蚀裂缝导流能力测试装置探究了酸液类型、酸液浓度、注入速率、酸刻蚀时间、岩性分布、渗透率分布、裂缝性质、温度、H^+传质系数、酸液与压裂液交替级数等因素对酸蚀裂缝导流能力的影响,认为高黏酸液有利于降低酸液滤失,并可能减少酸蚀坑的数量及大小,提高酸浓度有利于加深裂缝面的刻蚀和提高导流能力,增加酸刻蚀时间和注入速率可能出现点状、沟槽、均匀刻、沙滩状蚀形貌。岩性及渗透率空间分布在一定程度上决定着酸蚀裂缝形貌,粗糙岩板面在酸刻蚀后的导流能力高于光滑岩板面,高温使得白云岩的酸-岩反应由表面或混合控制转变成传质控制,酸液与压裂液多级交替注入有利于加深非均匀刻蚀,岩性和力学性质差异可能使得灰岩导流能力低于白云岩。现有酸蚀裂缝导流能力实验温度和闭合应力分别最高达180 ℃和70 MPa,而蓬深6井灯二段温度和闭合应力分别高达约200 ℃和90 MPa,已无法满足深层、超深层海相碳酸盐岩储层酸压改造物理模拟实验需求。此外,高闭合应力下酸蚀裂缝高导流能力的保持也成为十分关键的问题。

李年银等[23]、苟波等[24]、陈星宇等[25]、龚云蕾等[26]、GOMAA等[27]系统性阐述了各种酸蚀裂缝导流能力计算模型及特点,认为酸蚀裂缝导流能力模型可分为4类。第一类为基于导流实验数据简单拟合的方程,适用性非常有限;第二类为N-K模型及衍生模型[28-30],其通过酸溶蚀量计算平均酸蚀缝宽,考虑闭合应力及岩石嵌入强度,典型方程为指数型,常高估酸蚀裂缝导流能力[31-33];第三类为通过提取酸蚀裂缝表面特征参数(如粗糙度、纵向及横向剖切曲边长度、纵向及横向曲折比等),并拟合导流实验数据建立方程[34-35];第四类为基于酸蚀裂缝刻蚀形貌,运用弹塑性力学理论计算闭合应力作用下酸蚀裂缝闭合量,再结合N-S方程(纳维-斯托克斯方程,简称N-S方程)计算酸蚀裂缝导流能力,该类是酸压模拟主流发展趋势[36-40]。

拟以四川盆地灯影组超深层海相碳酸盐岩岩样为研究对象,通过开展超高温(200 ℃)、高闭合应力(90 MPa)酸蚀裂缝导流能力实验,优化酸液体系及组合注入工艺;基于酸蚀裂缝激光扫描数据,构建酸蚀裂缝导流能力模型;将其耦合酸压裂缝扩展及刻蚀模型,数值模拟预测酸压裂缝导流能力,以指导酸压改造方案设计。

1 酸蚀裂缝导流能力实验

1.1 实验材料、条件及方法

由于井下取心岩样有限,实验使用四川盆地灯影组露头,温度为200 ℃,闭合应力介于5～90 MPa,注酸速率为50 mL/min,各组总酸液量为1.2 L。采用气田现场常用酸液体系,胶凝酸、常规酸、转向酸、降阻酸及其组合,不同酸液组合均分液量。采用实验室自研的高温高压酸蚀裂缝导流能力测试装置开展导流实验,采用三维激光扫描仪获取裂缝刻蚀形貌,如图1所示。

1.2 实验结果及分析

不同闭合应力、酸液及组合下酸蚀裂缝导流能力如图2所示。随着闭合应力增大,导流能力总体呈现降低趋势,不同酸液及组合的降低模式有较大区别。当闭合应力为5 MPa时,导流能力较强,介于292～622 μm^2·cm;当闭合应力为90 MPa时,多数酸液及组合的导流能力较5 MPa时降低了一个数量级。导流能力随闭合应力的增加先出现第一个快速下降期,随后进入第一个缓慢下降期,后续是否出现第二个快速下降期,取决于第一个缓慢下降期的导流能力大小;当闭合应力大于50～60 MPa

a.高温高压酸蚀裂缝导流能力测试装置　　b.三维激光扫描仪

图1　酸蚀裂缝导流能力实验设备

Fig. 1　Acid-etched fracture conductivity testing equipment

时,高导流裂缝(如降阻酸+常规酸、降阻酸+胶凝酸、常规酸)的导流能力会出现一个较大降幅,即第二个快速下降期;闭合应力小于40 MPa时,组合酸液的导流能力均高于单独酸液;闭合应力增大至90 MPa时,降阻酸+常规酸、降阻酸+胶凝酸的导流能力高于单独酸液。因此,通过不同酸液组合注入,可在一定程度上改善超高温、高闭合应力下酸蚀裂缝导流能力。

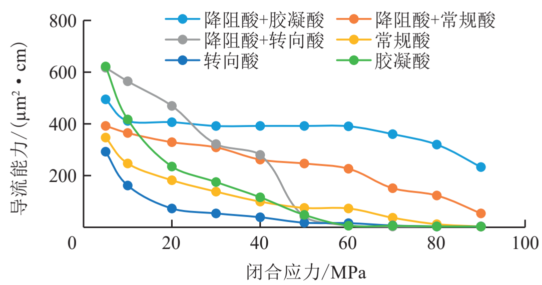


图2 四川盆地灯影组岩样不同闭合应力下酸蚀裂缝导流能力

Fig. 2 Results of acid-etched fracture conductivity under different closure stresses of Dengying Formation in Sichuan Basin

无闭合应力作用下酸刻蚀裂缝形貌三维激光扫描结果如图3所示,降阻酸+常规酸以沙滩状和点状刻蚀为主,降阻酸+胶凝酸以点状和沟槽状刻蚀为主,结合图2分析,数量众多的细小沟槽有助于在高闭合应力下保持导流能力。

2 酸蚀裂缝导流能力数值计算

2.1 数学模型

酸压施工停泵后,裂缝内净压力逐渐降至零,作用在酸蚀裂缝面上的有效闭合应力逐渐增大至某一稳定值。在此期间,酸蚀裂缝的2个面会产生第一个接触点,后续接触点数量随着闭合应力的增大而增多。以降阻酸+常规酸刻蚀裂缝形貌三维激光扫描结果为例,在缝长任意位置沿缝高方向取一横截面分析该过程,如图4所示,用椭圆表征未接触区[41],椭圆数量会随着闭合应力增大而有一定增加。

如图4b所示,椭圆长轴$2g$沿z方向,等于最大缝高,短轴$2d$沿y方向,等于最大缝宽。假设裂缝闭合为弹性变形,岩体应变方程为:

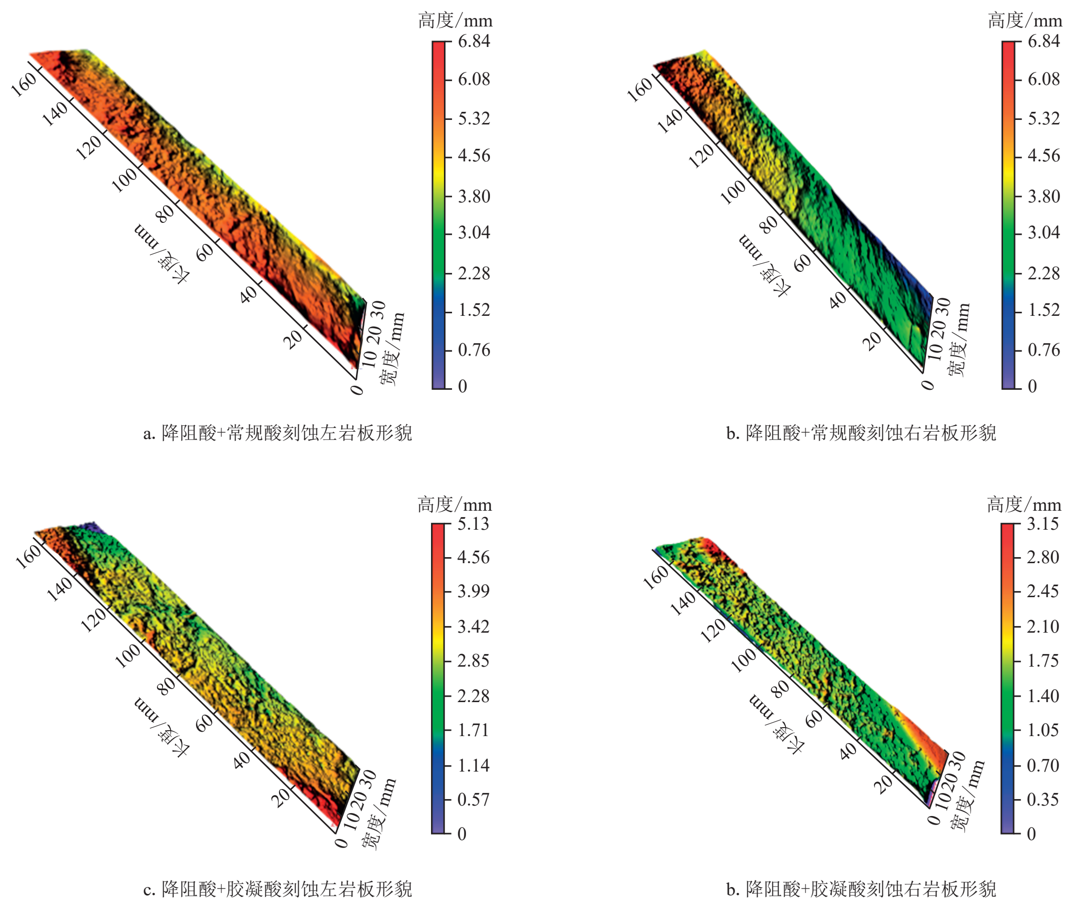


图3 四川盆地灯影组岩样酸刻蚀裂缝形貌三维激光扫描图

Fig. 3 Three-dimensional laser scanning image of acid-etched fracture morphology of Dengying Formation in Sichuan Basin

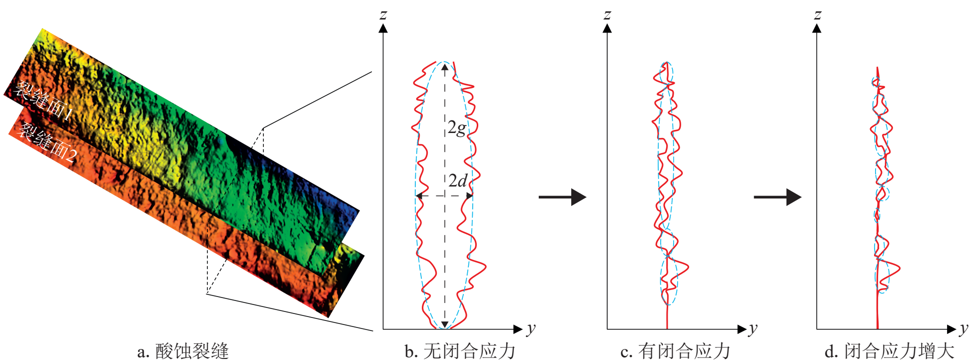


图4 闭合应力作用下酸蚀裂缝闭合示意图

Fig. 4 Schematic diagram of acid-etched fracture closure under closure stress

$$2\frac{\partial^2 \varepsilon_{yz}}{\partial y \partial z} = \frac{\partial^2 \varepsilon_{yy}}{\partial y^2} + \frac{\partial^2 \varepsilon_{zz}}{\partial z^2} \tag{1}$$

式中：ε_{yz}、ε_{yy}和ε_{zz}为应变分量。

将应力-应变关系代入式（1），得到：

$$(\kappa + 1)\left[\frac{\partial^2 \tau_{yy}}{\partial z^2} + \frac{\partial^2 \tau_{zz}}{\partial y^2}\right] + (\kappa - 3)\left[\frac{\partial^2 \tau_{yy}}{\partial y^2} + \frac{\partial^2 \tau_{zz}}{\partial z^2}\right] = 8\frac{\partial^2 \tau_{yz}}{\partial y \partial z} \tag{2}$$

式中：τ_{yz}、τ_{yy}和τ_{zz}为应力分量，单位Pa；κ为Muskhelishvili系数。

对于平面应变，κ=3−4v；对于平面应力，κ=(3−v)/(1+v)，v为泊松比。应力平衡方程微分形式为：

$$\left[\frac{\partial^2 \tau_{yy}}{\partial z^2} + \frac{\partial^2 \tau_{zz}}{\partial y^2}\right] + \rho\left[\frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z}\right] = -2\frac{\partial^2 \tau_{yz}}{\partial y \partial z} \tag{3}$$

式中：F_y和F_z为各方向上的体力，单位N/kg；ρ为密度，单位kg/m^3。

将式（3）代入式（2），并用函数U表征3个应力分量，假设无体力，便可得出Airy应力函数：

$$\begin{cases} \nabla^4 U = 0 \\ \tau_{yy} = \dfrac{\partial^2 U}{\partial z^2},\ \tau_{zz} = \dfrac{\partial^2 U}{\partial y^2},\ \tau_{yz} = -\dfrac{\partial^2 U}{\partial y \partial z} \end{cases} \tag{4}$$

使用复变量法求解Airy应力函数，表达式为[42]：

$$\begin{cases} U = \dfrac{1}{2}\left[\bar{x}\psi(x) + x\overline{\psi(x)} + \zeta(x) + \overline{\zeta(x)}\right] \\ 2G(u + is) = \kappa\psi(x) - x\overline{\psi'(x)} - \overline{\zeta'(x)} \\ x = z + iy \\ \bar{x} = z - iy \end{cases} \tag{5}$$

式（4）—式（5）中：U为应力函数，单位N；G为剪切模量，单位Pa；$\psi(x)$和$\zeta(x)$为2个解析函数；u和s为2个位移矢量；i为虚数单位。

满足应力边界条件的$\psi(x)$和$\zeta(x)$可表示为[43]：

$$\begin{cases} \psi(x) = \dfrac{\sigma_c c}{4}\left\{\exp\left(2\xi_0 + 2ir\right)\cosh\varsigma + \left[1 - \exp\left(2\xi_0 + 2ir\right)\right]\sinh\varsigma\right\} \\ \overline{\zeta'(x)} = -\dfrac{\sigma_c c}{4\sinh\varsigma}\left[\cosh 2\xi_0 - \cos 2\gamma + \exp\left(2\xi\right)\sinh 2\left(\varsigma - \xi_0 - i\gamma\right)\right] \\ \overline{\psi'(x)} = \dfrac{\sigma_c}{4}\left\{\exp\left(2\xi_0 - 2ir\right) + \left[1 - \exp\left(2\xi_0 - 2ir\right)\right]\coth\left(\xi - i\eta\right)\right\} \end{cases} \tag{6}$$

式中：σ_c为闭合应力，单位Pa；c为椭圆焦点；ξ_0为宽度，单位m；ξ、η分别为椭圆坐标系的坐标轴；ς=ξ+$i\eta$；γ为σ_c与椭圆长轴之间的夹角，单位rad。

采用笛卡尔坐标系(y, z)与椭圆坐标系(ξ, η)，椭圆边界上$\xi = \xi_0$。闭合应力垂直于裂缝面，γ=π/2；缝宽远小于缝长和缝高，对于薄裂缝，$\xi = \xi_0$=0，coshς=z/c，将式（6）代入式（5），得：

$$s = \frac{(\kappa + 1)\sigma_c}{4G}\left(g^2 - z^2\right)^{0.5} \tag{7}$$

式中：g为椭圆长轴半径，单位m。

式（7）无法处理多个椭圆，只适用于图4b所示情况；当有多个（m个）椭圆时，如图4c和图4d所示，将其视作椭圆集合[44]，沿缝高方向围绕每个椭圆以长2h_j划分m个单元，缝高一般远大于缝宽，在平面应变（κ=3−4v）下，使用应变能法，并对三角函数和对数函数的展开式取主导项，得到椭圆短轴形变量为：

$$\delta = \frac{\pi\sigma_c g^2}{2Gh_j}(1 - v) \tag{8}$$

式中：δ为椭圆短轴形变量，单位m；h_j为第j个椭圆所占缝高，单位m，j = 1, ..., m。

定义参数平均椭圆半长和裂缝接触比：

$$\bar{g} = \frac{\sum_{j=1}^{m} g_j}{m} \tag{9}$$

$$\lambda = 1 - \frac{\sum_{j=1}^{m} 2g_j}{H} \tag{10}$$

式(9)—式(10)中：$\bar{g}$为平均椭圆半长，单位m；m为椭圆个数；g_j为第j个椭圆长轴半径，单位m；λ为裂缝接触比；H为缝高，单位m。

用$\bar{g}$和λ表征闭合应力作用下酸蚀缝宽减小量为：

$$\Delta w = \frac{\pi \sigma_c \bar{g}}{2G}(1 - v)(1 - \lambda) \tag{11}$$

式中：Δw为酸蚀缝宽减小量，单位m。

若Δw大于w_{min}，意味着会有新的裂缝部位接触闭合，每个单元的缝宽减去w_{min}，得到新的缝宽分布，更新w_{min}数值，椭圆变得越来越小，会有椭圆消失或新产生(图4b—图4d)，直到Δw小于等于w_{min}，剩下椭圆的位置即为流动通道。假设裂缝为2个平行板，使用立方定律便可直接计算出整条酸蚀裂缝的导流能力为：

$$C_f = \frac{w^3}{12} \tag{12}$$

式中：C_f为酸蚀裂缝导流能力，单位$\mu m^2 \cdot cm$；w为酸蚀缝宽，单位m。

然而，用式(12)计算得到的酸蚀裂缝导流能力在低闭合应力下明显低于实验结果，而在高闭合应力下高于实验结果，其原因是酸蚀裂缝表面凹凸不平导致。使用细网格划分裂缝，在单个网格内可将2个裂缝面近似为平行，在单个网格内便可使用立方定律，即局部立方定律，单个网格渗透率可表示为：

$$k_f = \frac{w^2}{12} \tag{13}$$

式中：k_f为单个网格渗透率，单位μm^2。

对于每个网格，使用局部立方定律计算缝长和缝高方向的压力及流量：

$$\begin{cases} \frac{\partial}{\partial x}\left(w^3 \frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial z}\left(w^3 \frac{\partial p}{\partial z}\right) = 0 \\ q_x = \frac{w^3 l_x}{12\mu} \frac{\partial p}{\partial x},\ q_z = \frac{w^3 l_z}{12\mu} \frac{\partial p}{\partial z} \end{cases} \tag{14}$$

式中：p为单元压力，Pa；l_x和l_z分别为x和z方向单元长度，单位m；q_x和q_z分别为x和z方向单元流量，单位m^3/s；μ为黏度，单位Pa·s。

则酸蚀裂缝导流能力为：

$$C_f = \frac{q\mu L}{H\Delta p} \tag{15}$$

式中：q为流量，单位m^3/s；L为缝长，单位m；Δp为压差，单位Pa。

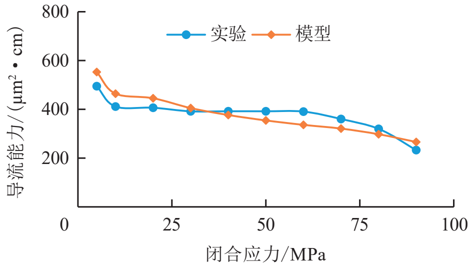
XUE等[45]以四川盆地灯影组为例，建立了考虑酸液动态滤失、矿物及孔渗非均匀分布、酸液刻蚀的酸压模型，并使用10余口井验证了模型的准确性。因此，基于XUE模型得到的酸压裂缝壁面刻蚀形貌，可以数值计算酸蚀裂缝导流能力，形成一套完整的酸压裂缝扩展、滤失、刻蚀、导流能力预测模型。

2.2 模拟结果及分析

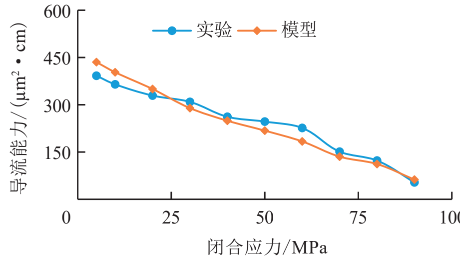
基于酸蚀裂缝三维激光扫描数据，利用模型分别计算出不同闭合应力下降阻酸+胶凝酸、降阻酸+常规酸的导流能力，并与实验结果进行对比(图5)。

图5显示降阻酸+胶凝酸、降阻酸+常规酸的模型计算结果与实验结果误差分别介于3.4%～14.2%和4.8%～18.9%，平均误差分别为9.7%和10.6%，不同闭合应力下模型与实验结果变化趋势一致，吻合良好，证实了酸蚀裂缝导流能力模型的正确性。

使用蓬深6井地质数据，分别模拟灯二段8 830～8 860 m和灯影组四段(以下简称灯四段)7 920～8 065 m酸压，使用88.9 mm油管注入，灯二段和灯四段的闭合应力分别为89.7、79.1 MPa，其余参数设置相同(排量为5.0 m^3/min，液量为450 m^3)，模拟得到酸压裂缝导流能力预测结果如图6所示。



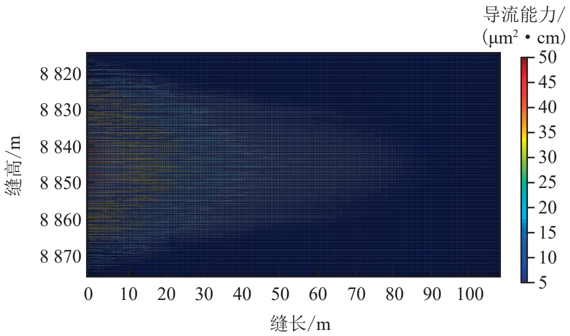
a.降阻酸+胶凝酸



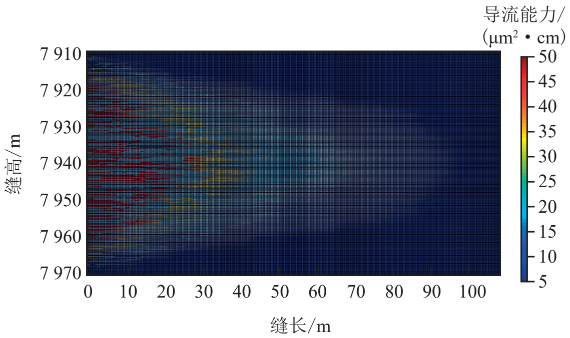
b.降阻酸+常规酸

图5 模型与实验结果对比

Fig. 5 Comparison of model and experimental results



a. 灯二段



b. 灯四段

图6 酸压裂缝导流能力模拟结果

Fig. 6 Simulation results of acid-fracturing conductivity

图6表明灯二段酸压整条裂缝的导流能力明显小于灯四段,裂缝入口端导流能力明显高于裂缝中部和尖端,符合导流实验结果认识,刻蚀深,且获得支撑的部位,导流能力高,如图6a中缝长为35 m以内条带状所在位置导流最高。

3 结论

1)酸蚀裂缝导流能力随闭合应力增加总体呈现降低趋势,不同酸液及组合的降低模式有较大区别,可能会出现2次快速下降阶段。90 MPa闭合应力下多数酸液及组合的导流能力较5 MPa时降低了一个数量级。

2)通过不同酸液组合注入,如降阻酸+常规酸、降阻酸+胶凝酸,可在一定程度上改善超高温和高闭合应力下酸蚀裂缝导流能力。

3)形成了酸蚀裂缝导流能力计算方法,模型与实验结果吻合度高,相对误差小。相同工程参数条件下,灯四段酸压裂缝导流能力较灯二段更高。

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