

裂缝性储层射孔井起裂压力影响因素分析*

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摘要: 水力压裂是目前最为常用、有效的储层增产措施。为了更好地进行压裂优化设计,提高储层改造效果,需要开展水力压裂裂缝起裂和扩展机理研究。裂缝性储层发育大量天然裂缝,具有强均质性,导致该类储层水力裂缝起裂与延伸规律复杂,具有强不确定性。因此,该文针对裂缝性地层起裂机制,基于张性起裂准则,考虑天然裂缝数量、产状及射孔工程参数,建立裂缝性储层起裂压力预测模型。分析结果表明:天然裂缝面存在,易导致水力裂缝沿裂缝面起裂,从而降低起裂压力。尤其随裂缝数量增加,起裂压力下降趋势更为明显。同时,起裂压力分布受工程参数控制,在高方位角和低井斜角条件下,起裂压力较大。研究成果对裂缝性储层压裂作业具有一定理论指导意义。

关键词: 裂缝性储层; 水力压裂; 射孔; 起裂压力

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引言

储层起裂压力预测是压裂优化设计的重要基础参数,对实现高效水力压裂具有重要影响。受地层非均质影响,地层起裂压力预测一直是水力压裂理论研究的难点问题^[1]。在天然裂缝发育的裂缝性储层,该问题尤为突出。

针对起裂压力的研究,由来已久。最早的预测模型建立在均质地层裸眼井条件下。随着近年来射孔完井技术的发展,金衍、朱海燕、郭建春等^[2-4]将射孔孔眼看作一个与井筒相连的小裸眼井,建立了射孔孔眼下的起裂压力模型,并对不同射孔方位、射孔深度、井眼轨迹下的起裂压力变化规律进行了分析。以上模型均建立在均质地层条件下,针对裂缝性地层起裂压力,目前的研究均基于单一弱面假设,以张性起裂准则,分析天然裂缝对起裂压力的影响,认为弱面存在条件下,地层可能沿岩石本体起裂或弱结构面起裂^[5-6]。该方法得到很好的应用,但不足之处在于裂缝性地层天然裂缝大量发育且随机分布,导致在该类储层射孔完井时,必然与多条天然裂缝相交,对起裂压力作用机制也更为复杂,单一弱面并不具有很好的适用性。因此,本文基于多条裂缝与孔眼的空间关系,建立起裂压力预测模型,分析起裂压力变化规律,从而认识裂缝性储层的水力裂缝起裂特征。

1 射孔孔眼围岩应力场分布

射孔孔眼围岩应力场是分析起裂压力的基础。本文基于常用假设,将孔眼看作一个小裸眼

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井与井筒相连.对任意井筒,井眼轨迹由井斜角和方位角控制,原地应力采用三向主应力描述.通过井眼坐标转换,视地层为线弹性连续介质^[7],建立井壁围岩应力分布如下:

$$\left\{ \begin{aligned} \sigma_r &= \frac{r_w^2}{r^2} p_i + \sigma_{xy} \left(1 + 3 \frac{r_w^4}{r^4} - 4 \frac{r_w^2}{r^2} \right) \sin(2\theta) + \\ &\quad \frac{\sigma_{xx} - \sigma_{yy}}{2} \left(1 + 3 \frac{r_w^4}{r^4} - 4 \frac{r_w^2}{r^2} \right) \cos(2\theta) + \\ &\quad \frac{\sigma_{xx} + \sigma_{yy}}{2} \left(1 - \frac{r_w^2}{r^2} \right), \\ \sigma_\theta &= -\frac{r_w^2}{r^2} p_i + \frac{\sigma_{xx} + \sigma_{yy}}{2} \left(1 + \frac{r_w^2}{r^2} \right) - \frac{(\sigma_{xx} - \sigma_{yy})}{2} \left(1 + 3 \frac{r_w^4}{r^4} \right) \cos(2\theta) - \\ &\quad \sigma_{xy} \left(1 + 3 \frac{r_w^4}{r^4} \right) \sin(2\theta), \\ \sigma_z &= \sigma_{zz} - 2\nu \left[(\sigma_{xx} - \sigma_{yy}) \frac{r_w^2}{r^2} \cos(2\theta) + 2\sigma_{xy} \frac{r_w^2}{r^2} \sin(2\theta) \right], \\ \tau_{r\theta} &= \sigma_{xy} \left(1 + 2 \frac{r_w^2}{r^2} - 3 \frac{r_w^4}{r^4} \right) \cos(2\theta), \\ \tau_{z\theta} &= \sigma_{yz} \left(1 + \frac{r_w^2}{r^2} \right) \cos \theta - \sigma_{xz} \left(1 + \frac{r_w^2}{r^2} \right) \sin \theta, \\ \tau_{rz} &= \sigma_{xz} \left(1 - \frac{r_w^2}{r^2} \right) \cos \theta + \sigma_{yz} \left(1 - \frac{r_w^2}{r^2} \right) \sin \theta, \end{aligned} \right. \quad (1)$$

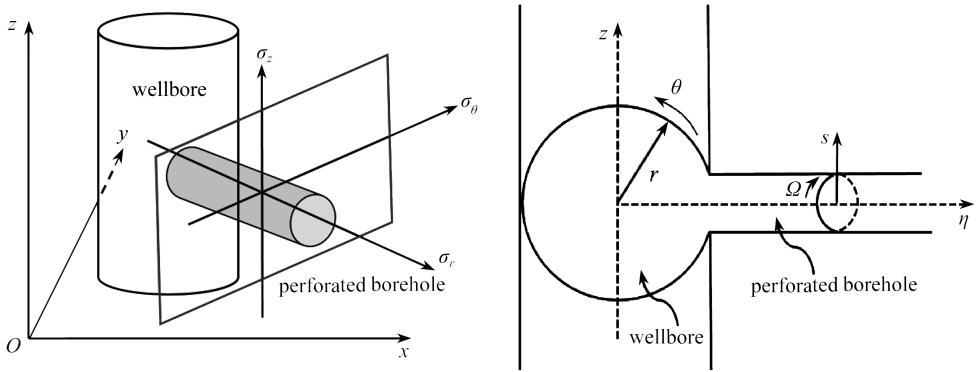
式中, $\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{xy}, \sigma_{yz}, \sigma_{xz}$ 为井筒坐标系下的原地应力分量, MPa; $\sigma_r, \sigma_\theta, \sigma_z$ 分别为井眼坐标系下径向、周向和轴向应力, MPa; $\tau_{r\theta}, \tau_{z\theta}, \tau_{rz}$ 为井眼坐标系下剪应力分量, MPa; θ 为井周角, ($^\circ$); p_i 为井筒液柱压力, MPa; r 为井眼径向距离, m; r_w 为井眼半径, m.

基于井筒围压受力状态与井筒和孔眼坐标系的相对关系(图1),认为孔眼围岩像井筒围岩一样的应力集中,在井底流体压力和井周应力作用下,孔眼周围应力分布如式(2)所示.

$$\left\{ \begin{aligned} \sigma_s &= \frac{r_{hs}^2}{s^2} P_{\text{perf}} + \tau_{\theta z} \left(1 + 3 \frac{r_{hs}^4}{s^4} - 4 \frac{r_{hs}^2}{s^2} \right) \sin(2\Omega) + \\ &\quad \frac{\sigma_\theta - \sigma_z}{2} \left(1 + 3 \frac{r_{hs}^4}{s^4} - 4 \frac{r_{hs}^2}{s^2} \right) \cos(2\Omega) + \\ &\quad \frac{\sigma_\theta + \sigma_z}{2} \left(1 - \frac{r_{hs}^2}{s^2} \right) + \left[\frac{\alpha(1-2\nu)}{2(1-\nu)} \frac{(s^2 - r_{hs}^2)}{s^2} - \phi \right] (P_{\text{perf}} - P_p), \\ \sigma_\Omega &= -\frac{r_{hs}^2}{s^2} P_{\text{perf}} + \frac{\sigma_\theta + \sigma_z}{2} \left(1 + \frac{r_{hs}^2}{s^2} \right) - \frac{(\sigma_\theta - \sigma_z)}{2} \left(1 + 3 \frac{r_{hs}^4}{s^4} \right) \cos(2\Omega) - \\ &\quad \tau_{\theta z} \left(1 + 3 \frac{r_{hs}^4}{s^4} \right) \sin(2\Omega) + \left[\frac{\alpha(1-2\nu)}{2(1-\nu)} \frac{(s^2 + r_{hs}^2)}{s^2} - \phi \right] (P_{\text{perf}} - P_p), \end{aligned} \right. \quad (2a)$$

$$\left\{ \begin{aligned} \sigma_{\eta} &= \sigma_r - 2\nu \left[(\sigma_{\theta} - \sigma_z) \frac{r_{hs}^2}{s^2} \cos(2\Omega) + 2\tau_{\theta z} \frac{r_{hs}^2}{s^2} \sin(2\Omega) \right] + \\ &\quad \left[\frac{\alpha(1-2\nu)}{1-\nu} - \phi \right] (P_{\text{perf}} - P_p), \\ \tau_{s\Omega} &= \tau_{\theta z} \left(1 + 2 \frac{r_{hs}^2}{s^2} - 3 \frac{r_{hs}^4}{s^4} \right) \cos(2\Omega) + \left(\frac{\sigma_{\theta} - \sigma_z}{2} \right) \left(1 + 2 \frac{r_{hs}^2}{s^2} - 3 \frac{r_{hs}^4}{s^4} \right) \sin(2\Omega), \\ \tau_{\eta\Omega} &= \tau_{zr} \left(1 + \frac{r_{hs}^2}{s^2} \right) \cos \Omega - \tau_{\theta r} \left(1 + \frac{r_{hs}^2}{s^2} \right) \sin \Omega, \\ \tau_{s\eta} &= \tau_{\theta r} \left(1 - \frac{r_{hs}^2}{s^2} \right) \cos \Omega + \tau_{zr} \left(1 - \frac{r_{hs}^2}{s^2} \right) \sin \Omega, \end{aligned} \right. \quad (2b)$$

式中, σ_s , σ_{Ω} , σ_{η} 为孔眼坐标系下径向、周向和轴向应力, MPa; $\tau_{s\Omega}$, $\tau_{\eta\Omega}$, $\tau_{s\eta}$ 为孔眼坐标系下三向剪应力, MPa; Ω 为孔眼上极坐标角, ($^{\circ}$); r_{hs} 为孔眼半径, m; s 为孔眼径向距离, m; P_{perf} 为孔眼流体压力, MPa; P_p 为孔隙压力, MPa; ϕ 为孔隙度, %; ν 为 Poisson(泊松)比; α 为 Biot 系数.



(a) 井筒围岩受力
(a) Stress state around the wellbore
(b) 孔眼与井筒坐标系
(b) Coordinates of the wellbore and the perforated borehole

图 1 井筒应力和射孔孔眼坐标系示意图

Fig. 1 The schematic of stress state around the wellbore and coordinates of the perforation and the wellbore

地层起裂前, 忽略孔眼的摩阻, 认为井筒流体压力与孔眼流体压力相等, 则在孔眼壁面上 ($s = r_{hs}$), 孔眼壁面应力分布为

$$\left\{ \begin{aligned} \sigma_s &= p_i - \phi(p_i - P_p), \\ \sigma_{\Omega} &= -p_i + (\sigma_{\theta} + \sigma_z) - 2(\sigma_{\theta} - \sigma_z) \cos(2\Omega) - 4\tau_{\theta z} \sin(2\Omega) + \\ &\quad \left(\frac{\alpha(1-2\nu)}{1-\nu} - \phi \right) (p_i - P_p), \\ \sigma_{\eta} &= \sigma_r - 2\nu [(\sigma_{\theta} - \sigma_z) \cos \Omega + 2\tau_{\theta z} \sin(2\Omega)] + \\ &\quad \left(\frac{\alpha(1-2\nu)}{1-\nu} - \phi \right) (p_i - P_p), \\ \tau_{\eta\Omega} &= 2\tau_{zr} \cos \Omega - 2\tau_{\theta r} \sin \Omega, \\ \tau_{s\Omega} &= \tau_{s\eta} = 0. \end{aligned} \right. \quad (3)$$

根据孔眼壁面受力状态,对任意井眼轨迹及孔眼方位条件下,孔眼壁面任意点三向主应力 $(\sigma_i, \sigma_j, \sigma_k)$ 如式(4)所示.基于上述主应力分布,采用张性破坏准则,则可获取起裂压力.

$$\begin{cases} \sigma_i = \sigma_s, \\ \sigma_j = \frac{1}{2}[\sigma_\Omega + \sigma_\eta + \sqrt{(\sigma_\Omega - \sigma_\eta)^2 + 4(\tau_{\eta\Omega})^2}], \\ \sigma_k = \frac{1}{2}[\sigma_\Omega + \sigma_\eta - \sqrt{(\sigma_\Omega - \sigma_\eta)^2 + 4(\tau_{\eta\Omega})^2}]. \end{cases} \quad (4)$$

2 裂缝性地层起裂压力模型

2.1 天然裂缝与主应力空间关系

裂缝性地层最大特点就是含有大量天然裂缝.天然裂缝面与孔眼壁面主应力空间关系会直接影响起裂压力^[8].因此,本文假设地层总共含有 k 个天然裂缝,任意裂缝面 i 的法线方向的矢量为

$$\begin{cases} \mathbf{n}_1(i) = \alpha_1(i)\mathbf{I} + \alpha_2(i)\mathbf{J} + \alpha_3(i)\mathbf{K}, \\ \alpha_1(i) = -\sin(D_p(i))\cos(A_z(i)), \\ \alpha_2(i) = \sin(D_p(i))\sin(A_z(i)), \\ \alpha_3(i) = \cos(D_p(i)), \end{cases} \quad i = 1, 2, 3, \dots, k, \quad (5)$$

式中, $\mathbf{n}_1(i)$ 为任意裂缝面 i 的法向矢量; $D_p(i)$ 是裂缝面 i 的倾角, $(^\circ)$; $A_z(i)$ 是裂缝面 i 的走向, $(^\circ)$.

孔壁任意一点,裂缝面 i 与孔壁主应力空间关系如图2所示.基于该空间关系,结合坐标变换原理,可以推导出大地坐标系下 σ_1 的方向矢量:

$$\begin{cases} \mathbf{n}_2(\sigma_1) = b_1(\sigma_1)\mathbf{I} + b_2(\sigma_1)\mathbf{J} + b_3(\sigma_1)\mathbf{K}, \\ b_1(\sigma_1) = \cos\theta\cos\Omega, \\ b_2(\sigma_1) = \sin\theta\cos\Omega, \\ b_3(\sigma_1) = \sin\Omega, \end{cases} \quad (6)$$

式中, σ_1 为最大主应力,MPa; $\mathbf{n}_2(\sigma_1)$ 为最大主应力方向矢量.

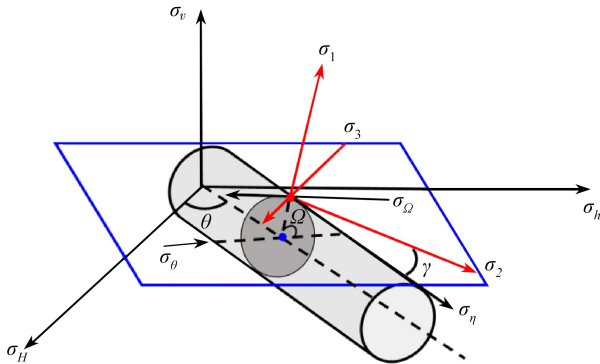


图2 孔眼壁面主应力与天然裂缝面空间关系

Fig. 2 Spatial relation between the principal stress of perforation and the natural fracture plane

基于同样空间转换原理,中间主应力 (σ_2 和最小主应力 σ_3) 的方向矢量分别为

$$\begin{cases} \mathbf{n}_2(\sigma_2) = b_1(\sigma_2)\mathbf{I} + b_2(\sigma_2)\mathbf{J} + b_3(\sigma_2)\mathbf{K}, \\ b_1(\sigma_2) = \sin(\theta + \psi) \sqrt{\cos^2\gamma + \sin^2\gamma \sin^2\Omega}, \\ b_2(\sigma_2) = -\cos(\theta + \psi) \sqrt{\cos^2\gamma + \sin^2\gamma \sin^2\Omega}, \\ b_3(\sigma_2) = -\cos\Omega \sin\gamma; \end{cases} \quad (7)$$

$$\begin{cases} \mathbf{n}_2(\sigma_3) = b_1(\sigma_3)\mathbf{I} + b_2(\sigma_3)\mathbf{J} + b_3(\sigma_3)\mathbf{K}, \\ b_1(\sigma_3) = \sin(\theta + w) \sqrt{\cos^2\gamma + \sin^2\gamma \sin^2\Omega}, \\ b_2(\sigma_3) = -\cos(\theta + w) \sqrt{\cos^2\gamma + \sin^2\gamma \sin^2\Omega}, \\ b_3(\sigma_3) = -\cos\Omega \sin\gamma, \end{cases} \quad (8)$$

式中, γ 为中间主应力与孔眼轴向夹角, ($^\circ$); ψ 和 w 的表达式为

$$\begin{cases} \psi = \arctan \frac{\sin\Omega \sin\gamma}{\cos\gamma}, \\ w = \arctan \left(-\frac{\sin\Omega \sin\gamma}{\cos\gamma} \right), \\ \gamma = \frac{1}{2} \arctan \frac{2\tau_{\eta\Omega}}{\sigma_\Omega - \sigma_\eta}. \end{cases} \quad (9)$$

综合上述分析,天然裂缝面 i 的法向方向与三个主应力夹角分别为

$$\cos \beta_j(i) = \frac{\mathbf{n}_1(i) \cdot \mathbf{n}_2(\sigma_j)}{|\mathbf{n}_1(i)| \cdot |\mathbf{n}_2(\sigma_j)|}, \quad i = 1, 2, 3, \dots, k; j = 1, 2, 3, \quad (10)$$

式中, $\beta_1(i)$, $\beta_2(i)$, $\beta_3(i)$ 为天然裂缝面 i 的法向与 $\sigma_1, \sigma_2, \sigma_3$ 的夹角。

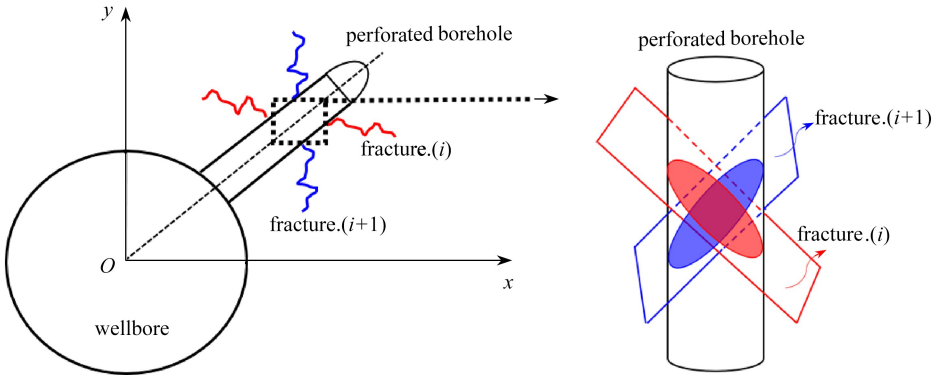


图3 孔眼与裂缝面相交关系

Fig. 3 Intersection relation between perforation and the natural fracture plane

2.2 起裂压力判断准则

本文针对起裂压力计算,依然基于张性起裂准则.射孔压裂时,孔眼会与多条裂缝面相交,如图3所示.该条件下,地层起裂压力与其起裂方式密切相关^[9].认为裂缝性地层岩石由岩石基体与裂缝面共同组成,沿岩石基体起裂与沿裂缝面起裂的判断准则如式(11)所示.基于式(11),在射孔孔眼内,对各点是沿裂缝面还是基体起裂进行判断最终选取最低压力值,即为起裂压力。

$$\begin{cases} \sigma_{\Omega} - \alpha P_p = S_t, & \text{failure across the rock matrix,} \\ P_{\text{perf}} = \sigma_n(i) - \alpha P_p, & \text{failure along the fracture plane,} \end{cases} \quad i = 1, 2, 3, \dots, k, \quad (11)$$

式中, S_t 为岩石抗张强度, MPa; $\sigma_n(i)$ 为裂缝面 i 的法向应力, MPa.

3 裂缝性地层起裂压力影响因素分析

3.1 裂缝产状对起裂压力的影响

基于本文模型, 首先以单一裂缝面为例, 不同裂缝产状下的起裂压力分布如图 4 所示. 由图可知, 沿基体破裂的起裂压力为 54.2 MPa, 沿基体破裂的范围为裂缝面倾向 $60^\circ \sim 90^\circ$ 和走向 $60^\circ \sim 120^\circ$. 而且在其他裂缝面产状条件下, 呈现沿裂缝面起裂方式. 当沿裂缝面起裂时, 起裂压力明显下降, 随裂缝面产状变化, 起裂压力呈复杂分布, 无明显规律性.

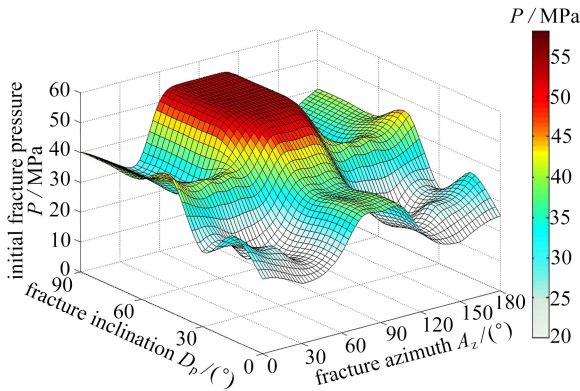


图 4 不同裂缝产状下的起裂压力分布

Fig. 4 Distribution of initiation pressure in different natural fracture occurrences

3.2 裂缝数量对起裂压力的影响

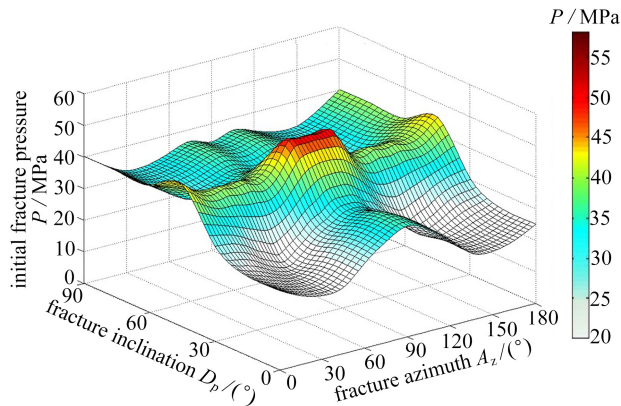
考虑到裂缝性地层天然裂缝面发育, 设置不同裂缝面数量, 假定裂缝面在大地坐标均匀分布, 以其中一条裂缝面产状为基准面, 起裂压力分布如图 5 所示. 由图可知, 随裂缝面数量增加, 整体起裂压力明显减小. 在两条裂缝时, 整体均沿裂缝面起裂, 起裂压力完全受裂缝面控制. 当裂缝面进一步增加, 起裂压力下降后趋于稳定. 当达到 4 条裂缝时, 相比较均质地层, 起裂压力平均下降 19.6 MPa.

天然裂缝在地层中具有任意分布特点, 多裂缝面条件下易形成非均匀分布特点. 但考虑到非均匀分布下, 多裂缝面会呈现多种分布特征, 极为复杂. 因此, 本文仅以一种非均匀分布条件下的起裂压力进行定性分析. 裂缝面产状分布如表 1 所示. 根据非均匀分布条件下的起裂压力计算结果(图 6)可知, 无论裂缝面的分布是否均匀, 越多裂缝面会造成更明显的起裂压力下降. 4 条非均质分布的裂缝面条件下, 相比较均质地层, 起裂压力下降 21.3 MPa.

表 1 多裂缝面条件下各裂缝面产状

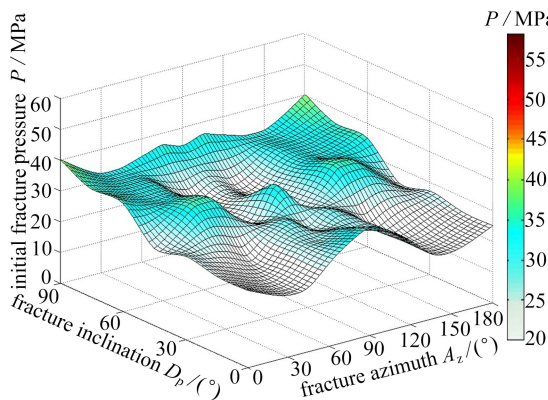
Table 1 Fracture occurrences of all fracture planes

fracture number	(dip, azimuth)/(°, °)	(dip, azimuth)/(°, °)	(dip, azimuth)/(°, °)	(dip, azimuth)/(°, °)
1	(0, 0)	-	-	-
2	(0, 0)	(15, 45)	-	-
3	(0, 0)	(15, 45)	(60, 75)	-
4	(0, 0)	(15, 45)	(60, 75)	(75, 120)



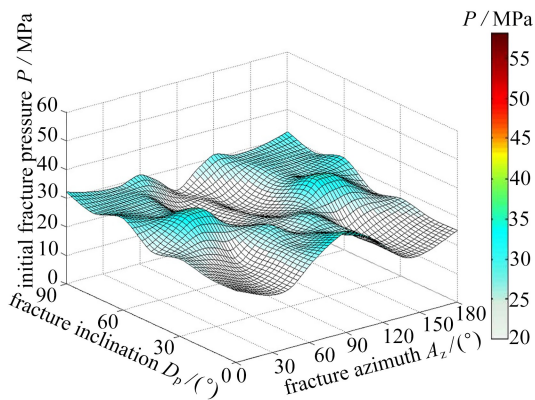
(a) 2 条裂缝面

(a) 2 fracture planes



(b) 3 条裂缝面

(b) 3 fracture planes



(c) 4 条裂缝面

(c) 4 fracture planes

图 5 不同裂缝数量下的起裂压力分布

Fig. 5 Distribution of initiation pressure in different natural fracture numbers

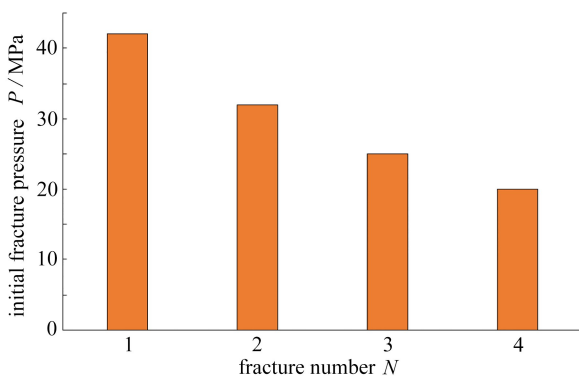


图 6 多条裂缝面非均匀分布下的起裂压力分布

Fig. 6 Distribution of initiation pressure in different natural fracture numbers with heterogeneous distribution

3.3 工程参数对起裂压力的影响

工程参数与压裂缝起裂、扩展密切相关^[10]。本文以射孔方位和井眼轨迹为例,对不同工程参数下的裂缝性地层起裂压力分布规律进行分析,如图7所示。由图可知,随射孔方位增加,起裂压力呈现增大趋势。随井眼倾角增大,起裂压力呈减小趋势。裂缝数量增大,整体起裂压力减小。3条裂缝面时,不同射孔方位与井斜角下的平均下降值为9.8 MPa和12.4 MPa。在多裂缝面条件下,整体起裂压力完全受裂缝面控制,由此表明裂缝面地层射孔优化设计时,地层裂缝面参数获取尤为重要。

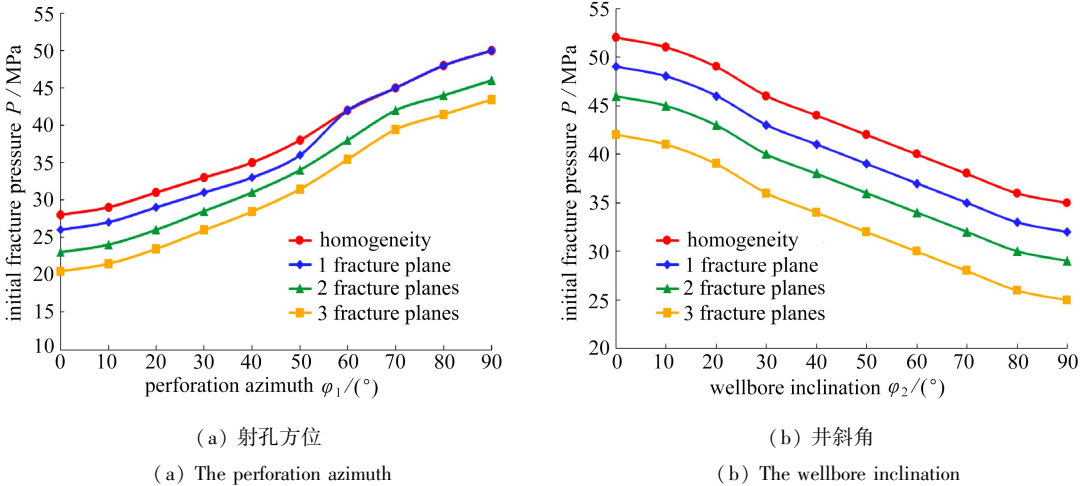


图7 地层起裂压力随工程参数变化规律

Fig. 7 Initiation pressure in different engineering parameters

4 结 论

1) 裂缝面存在时,地层可能沿基体与裂缝面起裂,从而导致起裂压力数值变化,尤其沿裂缝面起裂时,起裂压力会呈现明显下降。基于此,本文采用岩石张性破坏准则,考虑多组裂缝面条件,构建了射孔井眼起裂压力计算模型。

2) 基于该模型计算分析可知:沿裂缝面起裂时,起裂压力与裂缝面产状密切相关。随裂缝面产状变化,起裂压力呈复杂分布。同时,当地层裂缝数量增大,裂缝对起裂压力影响增加,起裂压力明显下降。当达到4条裂缝时,相比较均质地层,起裂压力平均下降19.6 MPa。在多裂缝面条件下,整体起裂压力完全受裂缝面控制。

3) 除地层裂缝影响外,工程参数(射孔方位、井眼轨迹)对地层起裂压力有显著影响。随射孔方位增加,起裂压力呈现增大趋势。随井眼倾角增大,起裂压力呈减小趋势。整体起裂压力下降幅度较大,3条裂缝面时,不同射孔方位与井斜角下的平均下降值为9.8 MPa和12.4 MPa。而在多裂缝面条件下,起裂方式均沿裂缝面起裂,由此说明裂缝面地层射孔优化设计时,地层裂缝面性质为重要基础参数。

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Research on Influential Factors of Initiation Pressure in Fracture Formation for Perforated Boreholes

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Abstract: Hydraulic fracturing is the most common and effective stimulation treatment. To better the fracturing design and improve the stimulation treatment, the mechanism of fracture initiation and propagation was investigated. In fracture formation, lots of natural fractures exist, having strong anisotropy and causing extreme complication and uncertainty of fracture initiation and propagation. Therefore, the mechanism of fracture initiation was stressed with the tensile criterion to establish the initiation pressure model in view of the natural fracture number, the occurrence and the intersection between perforation and fracture. The results indicate that, the natural fracture tends to cause initiation along the fracture plane and decrease the initiation pressure. In particular, with an increasing number of fracture planes, this decline will be more significant. Besides, the distribution of initiation pressure is related to several engineering parameters. For a high perforation azimuth and a low wellbore deviation, the initiation pressure will be relatively larger. The findings can offer reference for hydraulic fracturing in application.

Key words: fracture formation; hydraulic fracturing; perforated borehole; initiation pressure

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