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利用相渗曲线探索递减率随含水率变化呈现的规律

马培申¹,孙宜丽¹,舒政²,谭夜强¹,余强³,张薇¹,吴长虎¹,齐勇²

(1.中国石化河南油田分公司勘探开发研究院,河南 南阳 474780;2.西南石油大学油气藏地质及开发工程全国重点实验室,四川 成都 610500;3.中国石化河南油田分公司采油一厂,河南 南阳 474780)

摘要:为探究油田开发过程中不同含水率阶段产量递减率的变化情况。基于相渗曲线,研究了递减率、含水上升率、含水率三者之间的关系,建立了注采平衡的条件下递减率与含水率的关系,最后针对厚层油藏Z和多层油藏S进行实例计算分析。研究结果表明:在注采平衡的理想条件下,某一含水率阶段递减率受采液速度、束缚水饱和度的共同影响。递减率随着含水率的上升呈抛物线式变化,且递减率与采液速度成正比关系。在油藏确定的条件下,产量递减率大小主要由采液速度的大小决定,可通过调整井网密度、注采井数比等影响采液速度的参数控制产量递减。通过建立递减率与含水率的变化关系,明确产量递减变化规律的影响因素,为减缓产量递减对策提供依据。

关键词:递减率;相渗曲线;含水率;含水上升率;采液速度

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Study on variation in decline rate with water cut using relative permeability curves

MA Peishen¹, SUN Yili¹, SHU Zheng², TAN Ye-qiang¹, YU Qiang³, ZHANG Wei¹, WU Chang-hu¹, QI Yong²

(1. Research Institute of Exploration and Development, Sinopec Henan Oilfield Company, Nanyang, Henan 474780, China;

2. State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, China;

3. No.1 Oil Production Plant, Sinopec Henan Oilfield Company, Nanyang, Henan 474780, China)

Abstract: To investigate the variation of production decline rate at different water cut stages during oilfield development, this study explored the relationship between decline rate, water cut rise rate, and water cut based on relative permeability curves. The relationship between decline rate and water cut under injection-production balance conditions was established, followed by computational analyses on a thick oil reservoir Z and a multi-layer oil reservoir S. The results showed that, under ideal injection-production balance conditions, the decline rate at a certain water cut stage was jointly influenced by liquid production rate and irreducible water saturation. The decline rate exhibited a parabolic trend with increasing water cut and was proportional to the liquid production rate. For a given reservoir under known conditions, the magnitude of the production decline rate was primarily determined by the liquid production rate and could be controlled by adjusting parameters such as well spacing density and the ratio of injection to production wells, which affected the liquid production rate. By establishing the relationship between decline rate and water cut, factors influencing production decline are clarified, providing a basis for strategies to mitigate production decline.

Keywords: decline rate; relative permeability curve; water cut; water cut rise rate; liquid production rate

在油田的整个开发过程中,油田产量一般要经过产量上升、产量稳定、产量下降3个阶段^[1-4]。油田进入开发中后期,含水上升速度加快,油田产量开始下降,自然递

减率高,稳产难度大^[5-7]。弄清产量递减规律对指导油田生产开发,采取相应的稳产措施尤为重要^[8-11]。关于油田产量的递减规律,目前所开展的研究大多是基于 Arps 递

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第一作者简介:马培申(1968—),男,本科,高级工程师,从事油气田开发研究工作。地址:河南省南阳市桐柏县埠江镇河南油田,邮政编码:474780。

E-mail: mapeishen@sina.com

通信作者简介:齐勇(1995—),男,在读博士研究生,主要从事化学驱提高采收率理论与工艺技术研究。地址:四川省成都市新都区新都大道8号,邮政编码:610500。E-mail: 2062478871@qq.com

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减规律建立递减率与时间的关系^[12-15]。除生产时间外,递减率还受开井数、产液量、含水上率等诸多因素的影响^[16-19]。假设开井数保持相对平稳的水平,则影响递减率的因素主要受产液量和含水上率的影响^[20-23]。

含水率和递减率作为评价油田开发产能的2个重要参数,根据二者的变化情况可及时提出相应的补产措施,保证油田的高效开发^[24-27]。油气相对渗透率曲线走势是流体流动控制过程中的重要参数,相渗曲线能够更加直观和清晰地反映油田的地层情况,通过研究相渗曲线与油井生产动态关系,是评价油井产能指标的关键^[28-30]。通过建立递减率与含水上率的关系及基于相渗曲线建立含水率与含水上率的关系,从而建立递减率随含水率的变化关系。以此明确产量递减变化规律的影响因素,为减缓产量递减对策提供依据。

1 递减率随含水率变化呈现的规律

1.1 产量递减规律

递减率是反映油田生产过程中某一阶段产量下降的程度,在注采平衡的条件下,定义为单位时间内产量递减的百分数,当递减时间为年时,递减率计算见式(1):

$$D = -\frac{dQ_o}{Q_o dt} \quad (1)$$

式中: D 为递减率,%; Q_o 为递减阶段初始年产油量,单位 10^4 t; t 为时间,单位a。

产液量可表示为产油量与产水量之和,即式(2):

$$Q_L = Q_o + Q_w \quad (2)$$

式中: Q_L 为递减阶段初始年产液量,单位 10^4 t; Q_w 为递减阶段初始年产水量,单位 10^4 t。

将式(2)变形代入式(1),可得递减率计算式,见式(3):

$$D = -\frac{d\left\{\left[\frac{(Q_L - Q_w)}{Q_L}\right]Q_L\right\}}{Q_o dt} \quad (3)$$

1.2 递减率与含水上率的关系

在注采平衡的条件下, Q_L 为常数,将式(3)变形并简化得式(4):

$$D = -\frac{Q_L d(1 - f_w)}{Q_o dt} = \frac{Q_L df_w}{Q_o dt} \quad (4)$$

式中: f_w 为含水率,%。

由式(4)变形得式(5):

$$\frac{df_w}{dt} = D \frac{Q_o}{Q_L} \quad (5)$$

而含水上率是指每采出1%的地质储量含水上升的百分数,可表示为式(6):

$$f_w' = \frac{df_w}{dR} \quad (6)$$

采出程度计算见式(7):

$$R = \frac{N_p}{N} \quad (7)$$

式(6)一式(7)中: f_w' 为含水上率,%; R 为采出程度,%; N_p 为累计产油量,单位 10^4 t; N 为地质储量,单位 10^4 t。

将式(7)代入式(6)并变形可得式(8):

$$f_w' = N \frac{df_w}{Q_o dt} \quad (8)$$

将式(5)代入式(8)并变形可得递减率与含水上率的关系,见式(9):

$$D = \frac{Q_L}{N} f_w' \quad (9)$$

根据采液速度的定义,将式(9)进一步简化得式(10):

$$D = V_L f_w' \quad (10)$$

式中: V_L 为产液速度,%。

1.3 含水上率与含水率的关系

根据油水两相渗流理论,在不考虑毛细力和重力的情况下,含水率计算见式(11):

$$f_w = \frac{1}{1 + \left(\frac{\mu_w}{\mu_o}\right)\left(\frac{k_{ro}}{k_{rw}}\right)} \quad (11)$$

式中: μ_w 为水相黏度,单位mPa·s; μ_o 为油相黏度,单位mPa·s; k_{rw} 为水相相对渗透率,%; k_{ro} 为油相相对渗透率,%。

将式(11)变形可得式(12):

$$\frac{k_{ro}}{k_{rw}} = \frac{1 - f_w}{f_w} \frac{\mu_o}{\mu_w} \quad (12)$$

式(12)又称为分流方程,当油藏水油黏度比(μ_w/μ_o)一定,含水率只取决于水油相对渗透率比值的大小,而相对渗透率比值是油藏含水饱和度的函数,所以含水率是含水饱和度的函数。

k_{ro}/k_{rw} 可表示为式(13):

$$\frac{k_{ro}}{k_{rw}} = a e^{-bS_w} \quad (13)$$

式中: a 为直线段的截距; b 为直线段的斜率; S_w 为含水饱和度,%。

式(13)中的系数 a 、 b 由岩石和流体的性质决定,岩石的渗透率、孔隙大小分布、流体黏度、界面张力、润湿性等不同, a 和 b 值不同,可用图解法或联立方程组求出。

联立式(12)、式(13)得到式(14):

$$a e^{-bS_w} = \frac{1 - f_w}{f_w} \frac{\mu_o}{\mu_w} \quad (14)$$

将式(14)等式两边取对数后变形可得式(15):

$$S_w = -\frac{1}{b} \ln\left(\frac{\mu_o}{a\mu_w} \frac{1 - f_w}{f_w}\right) \quad (15)$$

式(15)求导可得式(16):

$$\frac{dS_w}{df_w} = \frac{1}{b} \frac{1}{f_w(1-f_w)} \quad (16)$$

将式(16)变形后得到式(17):

$$\frac{df_w}{dS_w} = bf_w(1-f_w) \quad (17)$$

将采出程度计算式(7)变形可得到采出程度的另一种计算方法,见式(18):

$$R = 1 - \frac{B_{oi}(1-S_w)}{B_o(1-S_{wi})} \quad (18)$$

式中: B_o 为原始地层压力下的原油体积系数,%; B_{oi} 为开发过程中某一地层压力下的原油体积系数,%; S_{wi} 为束缚水饱和度,%。

式(18)求导,得到式(19):

$$\frac{dR}{dS_w} = \frac{B_{oi}}{B_o} \frac{1}{1-S_{wi}} \quad (19)$$

式(19)变形可得式(20):

$$\frac{dS_w}{dR} = \frac{B_o}{B_{oi}} (1-S_{wi}) \quad (20)$$

联立式(17)、式(20)可得含水上率与含水率的关系,见式(21):

$$f_w' = \frac{df_w}{dS_w} \frac{dS_w}{dR} = b \frac{B_o(1-S_{wi})}{B_{oi}} f_w(1-f_w) \quad (21)$$

在油田注水开发过程中,可认为 $B_o \approx B_{oi}$,则式(21)可简化为式(22):

$$f_w' = bf_w(1-f_w)(1-S_{wi}) \quad (22)$$

将式(22)代入式(10)可得递减率与含水率的关系,见式(23):

$$D = V_L b(1-S_{wi})f_w(1-f_w) \quad (23)$$

由式(23)可知,在某一含水阶段内递减率随含水率的变化呈抛物线式变化,递减率的大小受采液速度和原始含油饱和度共同影响。

2 典型油藏相渗曲线的求解

基于所推导的递减率与含水率的关系式,在不考虑岩石孔隙大小分布、流体黏度、界面张力、润湿性等因素的理想条件下,计算不同含水率下递减率的变化规律。

典型油藏油水相对渗透率曲线见图1。根据图1中油水相对渗透率曲线数据,结合式(13)计算并绘制油水相对渗透率比值与含水饱和度的关系图(图2)。

通过图解法可求得 $a=989.26$, $b=12.60$ 。由图1可知典型油藏相渗曲线条件下的束缚水饱和度为20%,设定采液速度分别为3%、4%、5%,将已知条件代入式(23),

即可得到一系列采液速度条件下,不同含水率所对应的递减率,绘制递减率与含水率的关系曲线见图3。

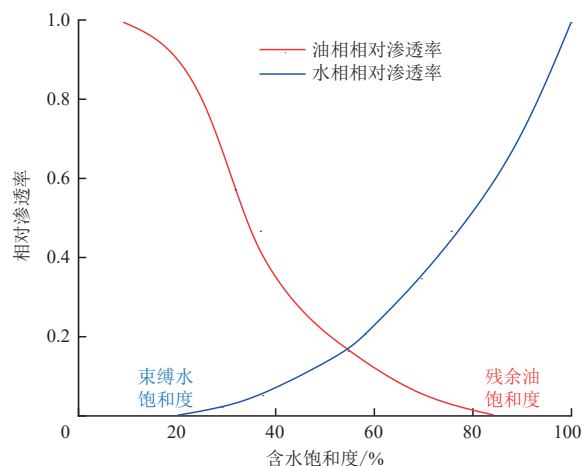


图1 典型油藏油水相对渗透率曲线

Fig. 1 Typical oil-water relative permeability curves for reservoirs

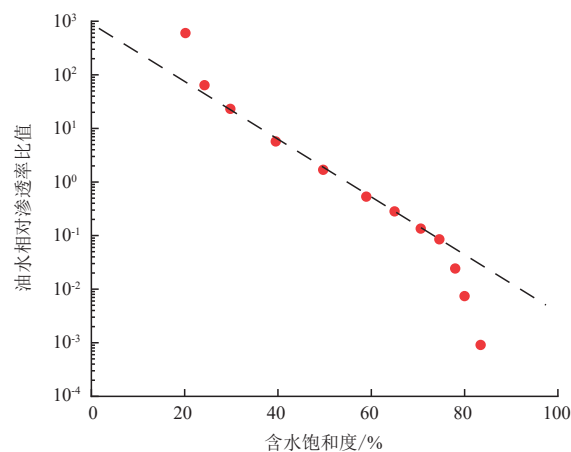


图2 油水相对渗透率比值与含水饱和度的关系

Fig. 2 Relationship between oil-water relative permeability ratio and water saturation

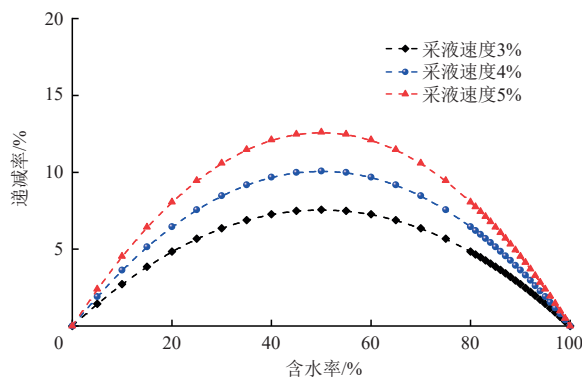


图3 不同采液速度条件下理论上递减率与含水率的关系曲线
Fig. 3 Theoretical relationship curves between decline rate and water cut under different liquid production rates

由图3可知,随着含水率的上升,递减率呈现出抛物线式变化规律,当含水率达到50%时,递减率达到峰值。在某一含水阶段内,采液速度越大递减率越大。

3 油田实例计算

3.1 厚层油藏Z

针对厚层油藏Z进行实例计算分析,选取厚层油藏Z最具代表性的相对渗透率曲线(图4)作为研究对象,根据图4中油水相对渗透率曲线数据结合式(13)计算并绘制厚层油藏Z油水相对渗透率比值与含水饱和度的关系见图5。

用图解法即可求得图6中 $b=16.35$,束缚水饱和度为30%,设定采液速度分别为4%、5%、6%、7%、8%,将已知条件代入式(23),得到厚层油藏Z不同含水率所对应的递减率,绘制递减率与含水率的关系曲线以及进入特高含水期后,不同采液速度条件下递减率与含水率的理论关系曲线以及厚层油藏Z实际递减率,见图6。

由图6可知,随着含水率的上升,厚层油藏Z递减率

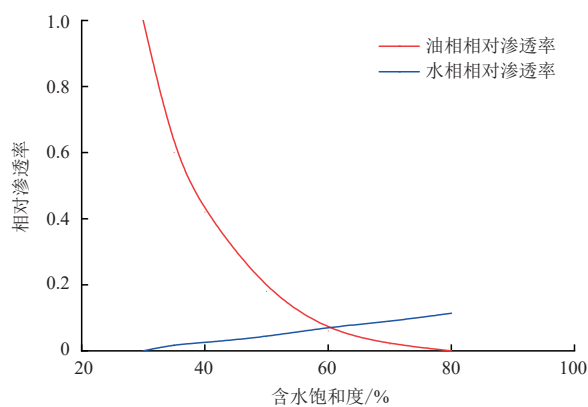


图4 厚层油藏Z的油水相对渗透率曲线

Fig. 4 Oil-water relative permeability curves for thick oil reservoir Z

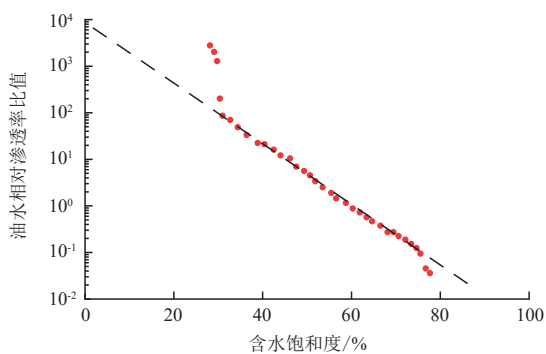


图5 厚层油藏Z油水相对渗透率比值与含水饱和度的关系
Fig. 5 Relationship between oil-water relative permeability ratio and water saturation for thick oil reservoir Z

同样呈现出抛物线式变化,在含水率达到50%时,递减率达到峰值。在某一含水阶段内,采液速度越大递减率越大。进入特高含水期后,厚层油藏Z实际递减率与预测递减率存在偏差,这是由于厚层油藏Z不同采液速度条件下递减率与含水率的理论关系曲线是在注采井网不发生变化且不考虑新井、措施井产量的情况下得到的理论值。

3.2 多层油藏S

针对多层油藏S进行实例计算分析,选取多层油藏S最具代表性的相对渗透率曲线(图7)作为研究对象,根据图7中油水相对渗透率曲线数据,结合式(13)计算并绘制多层油藏S油水相对渗透率比值与含水饱和度的关系见图8。

用图解法即可求得图8中 $b=22.28$,束缚水饱和度为29%,设定采液速度分别为4%、5%、6%、8%、10%,将已

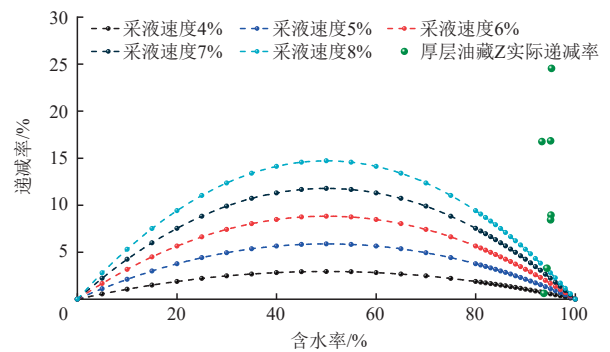


图6 厚层油藏Z不同采液速度条件下递减率与含水率的理论关系曲线及油藏实际递减率

Fig. 6 Theoretical relationship curves and actual decline rate between decline rate and water cut under different liquid production rates for thick oil reservoir Z

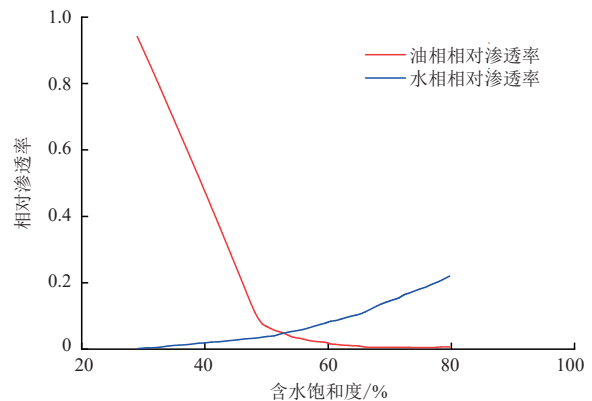


图7 多层油藏S的油水相对渗透率曲线

Fig. 7 Oil-water relative permeability curve for multi-layer oil reservoir S

知条件代入式(23),得到多层油藏S不同含水率所对应的递减率,绘制递减率与含水率的关系曲线以及进入特高含水期后,不同采液速度条件下递减率与含水率的理论关系曲线以及多层油藏S实际递减率见图9。

由图9可知,随着含水率的上升,多层油藏S递减率同样呈现出抛物线式变化,在含水率达到50%时,递减率达到峰值。在某一含水阶段内,采液速度越大递减率越大。进入特高含水期后,多层油藏S实际递减率与预测递减率存在偏差,这是由于多层油藏S不同采液速度条件下递减率与含水率的理论关系曲线是在注采井网不发生变化且不考虑新井、措施井产量的情况下得到的理论值。

通过厚层油藏Z和多层油藏S实际递减率与预测递减率的对比分析,二者之间存在一定的偏差,分析认为:在油田实际开发过程中由于不断有新井及措施井的投入以及注采井网的调整,导致进入特高含水期后实际递减

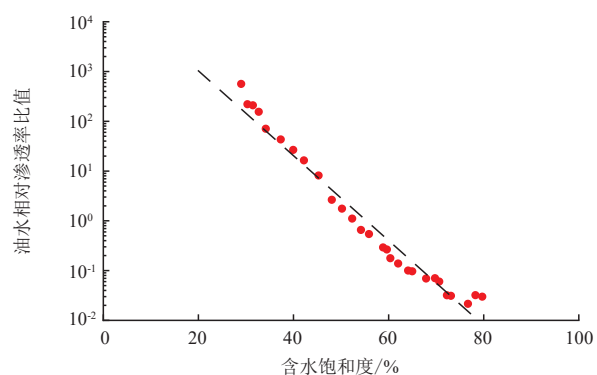


图8 多层油藏S油水相对渗透率比值与含水饱和度的关系
Fig. 8 Relationship between oil-water relative permeability ratio and water saturation for multi-layer oil reservoir S

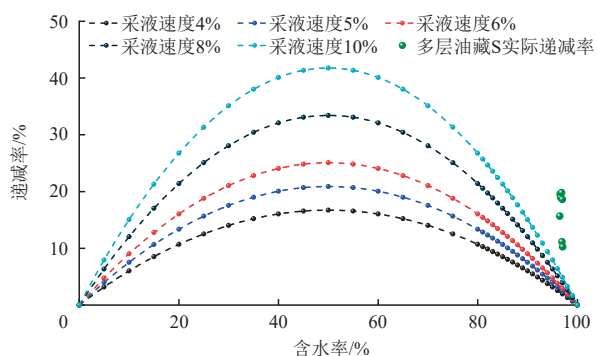


图9 多层油藏S不同采液速度条件下递减率与含水率的理论关系曲线及油藏实际递减率
Fig. 9 Theoretical relationship curve and actual decline rate between decline rate and water cut under different liquid production rates for multi-layer oil reservoir S

率与理论递减偏差较大。除此之外,当含水率大于90%以后,利用图解法所求 b 值偏小,导致求得的特高含水期递减率与含水率的关系存在误差,因此进入特高含水期后需要通过联立方程组的方式对 b 值进行逐一求解。

4 结论

1) 在油藏条件及开发条件确定的条件下,递减率与含水率呈抛物线关系,且递减率与采液速度成正比关系,在含水率达到50%时,递减率达到峰值。

2) 通过厚层油藏Z和多层油藏S实例计算以及对对比分析发现,由于新井及措施井的投入以及注采井网的调整,实际递减率与预测递减率之间存在一定的偏差。此外当含水率大于90%以后,利用图解法所求 b 值偏小,导致求得的特高含水期递减率与含水率的关系存在误差,因此,进入特高含水期后需要通过联立方程组的方式对 b 值进行逐一求解。

3) 在油藏确定的条件下,可通过调整井网密度、注采井数比等影响采液速度的参数控制产量递减。

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