·油气采收率·

面积劈分—叠加法预测聚合物驱后剩余油分布

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摘要:至2011年底,中国聚合物驱后的原油采出程度约为53%,聚合物驱后剩余油仍具有相当大的开采潜力,为使其得到有效开发,提出利用面积劈分—叠加法对聚合物驱后单井及整个区块的剩余油潜力分布进行预测。以大庆油区长垣北部典型聚合物驱油藏为例,研究了37口生产井的聚合物驱后剩余油分布规律。根据聚合物驱采出程度的变化,将聚合物驱后单井剩余油潜力划分为高、中、低3个等级。聚合物驱后剩余石油地质储量的平面分布表明,剩余油主要分布在区块主砂体带中井网控制程度弱的2大区域。

关键词:聚合物驱后 剩余油 分布规律 面积劈分—叠加法 采出程度
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目前,中国各大主力油田已陆续进入开发后期的四次采油阶段,该阶段以聚合物驱后接替技术和配套措施继续挖潜剩余油为主要特征[1]。随着开发程度的逐步加深,聚合物驱后残留在地层中的剩余油量逐渐减少,其分布越来越复杂,研究难度也越来越大[2]。

为了查清聚合物驱后剩余油的分布规律,需要采用多种方法进行研究,如精细地质研究、检查井及测井资料分析、室内物理模拟以及数值模拟等[3-8]。通过研究聚合物驱后剩余石油地质储量的分布,可以更为直观地反映聚合物驱后剩余油的富集规律及其潜力。但是,仅了解整个油藏的剩余石油地质储量已不能满足实际开发的需求,需要缩小剩余油的研究范围,针对某个沉积相带、单个砂体以及单井区域内的剩余石油地质储量,开展更为精细的描述和分析。为此,以容积法为基本原理[9-10],充分考虑单井控制石油地质储量的差异,提出了利用面积劈分—叠加法精细划分和计算聚合物驱后单井剩余石油地质储量。通过较为合理地描述大庆油区某典型聚合物驱油藏单井剩余石油地质储量的分布,研究和总结聚合物驱后单井剩余石油地质储量潜力以及平面剩余油的分布规律,将有助于指导该区块及其他同类油藏或区块的剩余油研究及后期开发方案调整。

1 区域概况

喇嘛甸油田北东块位于大庆油区长垣北部,含油面积为14.9 km^2,采用300 m×150 m的五点法聚合物驱注采井网进行开发。聚合物驱目的层位葡I1-2油层以大型砂质辫状河沉积为主,油层厚度大,平均有效厚度为13.3 m,渗透率高,平均有效渗透率为517.0×10^{-3} μm^2,层内、平面非均质性严重,划分为葡I1、葡$I2^1$、葡$I2^2$、葡$I2^3$共4个沉积时间单元。从地质特征的角度来讲,可以作为聚合物驱典型油藏的代表。

1995年末开展了聚合物驱现场试验,具体注入方案是:采用相对分子质量为$1\ 500\times10^4$的聚合物;年注入速度为0.19倍孔隙体积,聚合物用量为570 mg/L·PV;采用单一整体段塞,段塞质量浓度为1 000 mg/L。2000年末,研究区已进入后续水驱的特高含水开发阶段,虽经过多次注聚调整,井组见效差异仍然较大,受沉积韵律影响,发育较差的部位动用程度仍然较低。截至2009年末,累积增油量为358×10^4 t,试验虽已将采收率提高了12.6%,但到聚合物驱结束采收率不到50%,仍有一半以上的储量滞留在地下。聚合物驱后剩余油分布高度分散,开采难度加大。

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2 方法建立及计算

从实际情况考虑，单井控制面积与井点的疏密程度具有相关性，在井点密集的地方单井控制面积小，而在井点稀疏的地方单井控制面积大。根据这一规律，可采用三角网法来确定单井控制面积。

2.1 实施步骤

所谓三角网，就是用互不相交的直线段把所有井点连接起来而构成的一系列三角形[11-12]。三角网法是划分单井控制含油面积的基础。因此，按照基本原理与假设，建立了适用于划分聚合物驱单井控制含油面积的三角网法：① 将所有的注采井依次连接成三角网，连接时要选取互为邻近的井点，并尽量以锐角三角形为主要的形式；② 作每个三角形的中垂线，若中垂线之交点落在三角形之外，则以三角形中点连线划分；③ 把某一口井为中心的最邻近三角形的中垂线交点或三角形中线（对于钝角三角形）交点连接起来，就构成了这口单井的控制面积；④ 以注入井为中心井，直接把所有注入井单井面积劈分到生产井。这是因为注入井虽然不生产，但也有储量，该部分储量随着注入井的注水开发会流入生产井产出。

2.2 基本劈分原则

在实际操作时，还需要遵循一定的劈分原则：① 将该区块所有的77口井（40口注入井、37口生产井，其中包括2口转注井和1口停产井）绘于图中，选择最为邻近的3口井连接成三角形。② 对井位上所有的井按三角网法进行面积劈分，并在单井控制面积劈分时，尽量以三角形的中垂线作为单井控制面积的边界。③ 进行注入井劈分时，当2个注入井相邻时，以井位连线为界限，将其分割的2部分控制面积划分到相邻的采油井面积中。④ 对于靠近边界的注入井，由于其没有相应的油井进行面积分配，可采用镜像反映法，在边界外围假想出1个虚拟注入井进行劈分。这样，靠近边界处的相邻2口注入井之间的孔隙就为死孔隙，也就是注入流体驱替不到的地方。⑤ 对于在开采阶段转注的井，可一直按照水井对待，将其产量和储量都分配到附近的油井上。⑥ 对于开采阶段已经停注的井，也要参与面积劈分。虽然在井位图中仍要将其画出，但在最终的注入井储量重新分配的过程中将不参与划分。

2.3 单井控制面积的求取

根据井位坐标建立三角网后，将每个三角形的中垂线交点或中点连线所划分的区域连接起来就是单井控制面积。实际上单井控制面积是任意个四边形（视该井点处连接的三角形个数而定）的面积之和，而每个四边形则是一个面积劈分所封闭的区域，其面积为

$$S_t=\sqrt{(p-a)(p-b)(p-c)(p-d)-abcd\cos^2\alpha} \tag{1}$$

其中

$$p=\frac{1}{2}(a+b+c+d) \tag{2}$$

$$\alpha=\frac{1}{2}(\angle A+\angle C)=\frac{1}{2}(\angle B+\angle D) \tag{3}$$

式中：S_t 为四边形的面积，m^2；p 为四边形周长的二分之一，m；a，b，c，d 分别为四边形的边长，m；A，B，C，D 分别为四边形的4个内角，(°)；α 为对角之和的二分之一，(°)。

单井控制面积为

$$S=\sum_{t=1}^{n}S_t \tag{4}$$

式中：S 为单井控制面积，m^2/口；n 为某一井点处三角形的数量，个。

按照式(1)—式(4)，编制多边形面积计算软件。求取单井控制面积时，将以生产井为中心的各条边界线对应节点的 x 和 y 坐标整理成2列，并以对应生产井的井名作为区分的标志。用编制的任意多边形面积计算软件即可求得单井的控制面积。

2.4 剩余石油地质储量的求取

求出单井控制面积后，用单井控制面积乘以单储系数和砂岩有效厚度，就得到了单井控制石油地质储量。然后，将各单井控制石油地质储量减去累积产油量，即得单井的剩余石油地质储量。最终，将所有井的剩余石油地质储量进行叠加，即可得出聚合物驱后研究区所有井的剩余石油地质储量的分布。虽然应用该方法得到的是剩余石油地质储量的静态分布，但若与开发时间联系起来，就可得到不同开发阶段单井以及全区剩余石油地质储量的总体变化。

3 研究结果及分析

3.1 单井剩余石油地质储量分布

研究区37口生产井均参与产量劈分，剩余石油地质储量为 329.1×10^4 t，平均单井剩余石油地质储量为 9.68×10^4 t。其中，单井剩余石油地质储量大于 10×10^4 t的井有13口，占总井数的35.1%，储量约为总剩余石油地质储量的52.7%；单井剩余石油地质

储量为5×10⁴～10×10⁴ t的井有17口，占总井数的45.9%，储量约为总剩余石油地质储量的39.7%；单井剩余石油地质储量小于5×10⁴ t的井有7口，占总井数的18.9%，储量约为总剩余石油地质储量的7.6%。也就是说，有92.4%的单井剩余石油地质储量大于5×10⁴ t，累积剩余石油地质储量可占总储量的92.4%。由此可见，该区块剩余石油地质储量的开采潜力仍旧很大。

从聚合物驱阶段单井采出程度的变化规律（图1）可以看出，随着采出程度的增加，聚合物驱后单井剩余石油地质储量逐渐减少。但是，由于单井控制石油地质储量不同，也存在一些特殊情况。因此，若排除靠近区块边界的3口虚拟井，可以将余下的34口井进一步划分为以下3类。

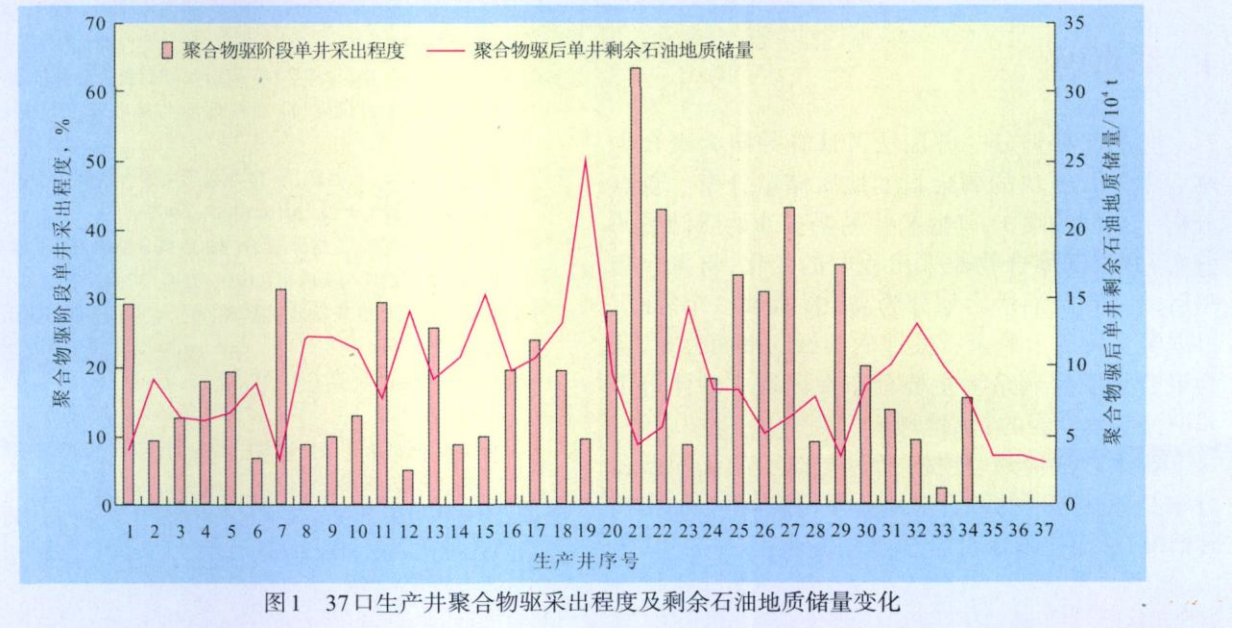

图1　37口生产井聚合物驱采出程度及剩余石油地质储量变化

聚合物驱采出程度低的高潜力类　这类井的聚合物驱采出程度较低，一般为2.4%～19.4%。其中，聚合物驱采出程度的最小值出现在L10–22井附近，最大值出现在L8–2035和L9–20井附近。此类生产井最多，总数达到21口，占总井数的61.8%，单井剩余石油地质储量均在10×10⁴ t以上，能够较好地反映整个区块的开发动态。

聚合物驱采出程度较高的中潜力类　这类生产井的聚合物驱采出程度较高，一般为20.2%～42.9%，平均值为30.7%。这类井中聚合物驱采出程度相对较低的是10–P193井，采出程度较高的是L9–P202和10–P203井。单井剩余石油地质储量较高，为5×10⁴～10×10⁴ t。井数达到9口，占总井数的26.5%。

聚合物驱采出程度高的低潜力类　在研究中发现，少数生产井附近聚合物驱采出程度较高，为28.8%～63.2%；L8–22井附近为最小值，L9–2015井附近为最大值。单井剩余石油地质储量相对较小，都小于5×10⁴ t。井数仅为4口，占总井数的11.8%。

3.2　油藏剩余石油地质储量的平面分布

平面上，研究区剩余石油地质储量富集区域主要可划分为2个部分：①生产井L8–P211，L9–P211和L9–2215井所包围的区域内的剩余石油地质储量均大于12×10⁴ t；② L9–P193井附近，区域剩余石油地质储量为12×10⁴～14×10⁴ t（图2）。

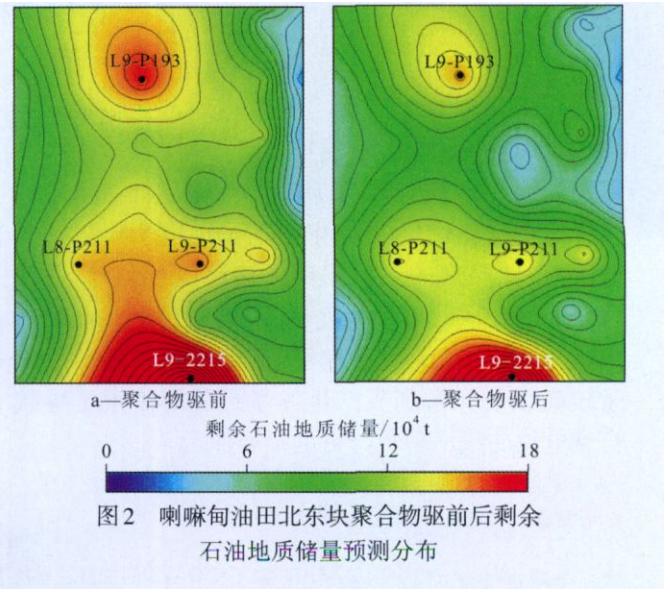

图2　喇嘛甸油田北东块聚合物驱前后剩余石油地质储量预测分布

分析平面剩余油的形成原因，认为这些剩余油较为富集的区域是在储层的沉积特征和开发措施的共同作用下形成的。从沉积微相图可以看出，研究区以河道砂和废弃河道砂为主，天然堤和决口席状砂也占有一定比例，且主要分布在研究区的南

部：从井网部署上看，在这2个区域内的井数较为稀少，井网控制程度也稍弱一些。因此，受到地质和开发因素的双重控制，聚合物驱后在该区块的上、下2个部位残留了较多的剩余油。由此可见，使用该预测方法所得结论与油田实际的地质特征和开发状况基本相符，初步说明了利用该方法研究剩余油的可行性。

4 结束语

应用面积劈分—叠加法可计算并研究聚合物驱后单井及区块的剩余石油地质储量分布。重点分析了典型油藏37口生产井剩余石油地质储量的分布，并根据聚合物驱采出程度的变化，将聚合物驱后单井剩余油潜力划分为高、中、低共3个等级。根据聚合物驱后剩余石油地质储量的平面分布，认为聚合物驱后剩余油主要分布在区块主砂体带中井网控制程度弱的2大区域。

新建方法简易、便捷，通过与储层的沉积微相分布及井网部署的综合对比分析，基本符合油田实际情况，从而初步证明了方法的可行性。

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性、微裂缝、流体性质、储层厚度、地层水矿化度和地层压力等因素的影响，认为自然电位曲线呈现的各种非正常变化是多种因素共同作用的结果：钻开地层时，储层内的地层水渗入井筒内，使井筒内钻井液滤液的矿化度发生变化，导致自然电位曲线出现漂移，储层段无异常显示；而泥岩地层碳酸盐含量较高以及异常高压产生的微裂缝等因素是导致自然电位曲线出现负异常的重要原因。

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depression, red mudstone's vertical structure and the relationship with sequence boundary are discussed herein. The mudstone in Es_4 of Yong 82 well mainly includes 4 types: red loose mudstone, red compact massive mudstone, dark grey banding mudstone and grey or grayish purple gypsum mudstone. The red loose mudstone has strong striated rock surface, and its chemical element combinations are close to paleosol. The mudstone's chemical index of alteration analysis indicates that the red loose mudstone has suffered low chemical paleo-weathering, its CIA tends to be lower from top to bottom, indicating rocks' chemical paleo-weathering tends to be lower when the depth increases. The top of the red loose mudstone is relative to the sequence boundary in Es_4. However, the grey sandstone with red mudstone in the top of early Es_4 should be attributed to upper sequence's low stand system.

Key words: Shahejie Formation; mudstone; geochemistry characteristics; sequence bounday; paleosol; Dongying depression

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Mu Xing. Seismic weak signal separation based on blind signal processing. *PGRE*, 2012,19(5):47-49.

Abstract: Blind signal processing technique is one of the hot topics in the field of modern signal processing, aiming at solving problems such as how to separate or estimate the waveforms of the original source from an array of sensors or transducers without or with little knowledge of original waveforms and the characteristics of transmission channels. This paper presents the application of blind signal processing technology to the extraction of seismic weak signals. Based on the investigation and analysis of the relationship between blind signal processing theory and seismic reflection features of subtle pool, an aliasing model of seismic blind-source signals is established in order to extract weak signals from seismic data of target reservoirs. At same time, two new strategies for weak signal extraction are proposed. Using reflection similarity among seismic traces of surrounding rocks and reflection differences of weak signals from target reservoirs, we developed an iterative algorithm for weak signals extraction. The results of simulation and seismic data processing show that the method can extract seismic weak signals successfully and thus improves the resolution of seismic data.

Key words: blind signal processing; seismic weak signal; resolution; blind source separation; subtle reservoir

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Pang Jiandong, Li Sanfu, Jia Cunfu et al. Speed laws and velocity field establishing in ocean deep water area-case of Baiyun sag. *PGRE*, 2012,19(5):50-53.

Abstract: he complexity of velocity structure in deepwater area leads to distortion of the sedimentary layer structure and the difficulty of depth forecast, and seriously hampered oil and gas exploration of the deepwater area. We analyze characteristics and influencing factors of velocity structure in the Baiyun sag, using AL velocity, VSP velocity, and recognize that there is no necessary relationship between formation velocity and the water depth, and the sedimentary environment essential difference between continental shelf, continental slope deep water area is the fundamental cause of the abnormal rate. Then, we buildup the depth conversion method suitable for the deepwater area of Baiyun sag, by use of the mutual restraint of drilling speed, velocity of coherent inversion and seismic stacking speed. This method resolves tectonic distortion due to rough subsea preferably, and improves depth-prediction accuracy considerably.

Key words: slope waters; velocity structure; coherent velocity inversion of pre-stack seismic; time-depth conversion velocity field; Baiyun sag

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Feng Hongxia, Lü Zengwei, Li Shaoxia et al. Influential factor of SP curve in upper Sha4 member, Chunhua oilfield. *PGRE*, 2012,19(5):54-56.

Abstract: The abnormal phenomena of the data of SP log appeared in the upper Sha4 member in Chunhua oilfield. Some reservoirs have been missed easily and the thickness of some reservoir is inaccurate during the process of identifying reservoir. Based on the theory of SP curve occur, some reasons are analyzed such as formation thickness, formation water salinity and lithological change. The result shows that the abnormal pressure, reservoir thickness, lithology and fluid property caused salt concentration unequal of drilling fluid when the formation was drilled, and this resulted in the anomaly drop of SP curve. In some reservoir, the mud filtrate salinity is more than formation water salinity, this caused SP curve anomaly positive. High carbonate content and microfracture caused by abnormal pressure are the main reasons resulted in SP curve anomaly negative in mudstone. The research obtained good effect in the process of production and improved the accuracy of the logging data interpretation.

Key words: upper Sha4 member; reservoir; mudstone; self-potential; diffusion-adsorption electrodynamic potential

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Wang Zhengbo, Ye Yinzhu, Wang Qiang et al. Forecast of remaining oil distribution after polymer flooding by area-split and superposition method. *PGRE*, 2012,19(5):57-60.

Abstract: Until the end of 2011, oil recovery after polymer flooding is about 53% in China. Residual oil reserves after polymer flooding own pretty high exploitation potential. In order to extract the amount of remaining oil efficiently, it's necessary to study residual oil law and its potential distribution after polymer flooding. For that reason, area-split and superposition method has been put forward specifically, which can be utilized in forecast and studying on residual oil potential distribution of single well and whole reservoir after polymer flooding. Then, the key reservoir in the north of Daqing placanticline is selected as a typical object. After that, the residual oil distribution law of 37 wells after polymer flooding is studied respectively. Finally, based on the changes of recovery

degree, 3 levels of single well's residual oil potential have been divided after polymer flooding, which can be classified as high, medium and low. According to planar distribution of residual oil geological reserves, 2 enrichment areas after polymer flooding, which are mainly located in prime sand body and weak well pattern controlling parts, are pointed out as well. The research process and results can provide certain methodological and theoretical references on the forecasting of residual oil and the rational adjustment and potential tapping after polymer flooding.

Key words: post-polymer flooding; residual oil; distribution law; area splitting and superposition; recovery degree

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Yao Chuanjin, Lei Guanglun, Gao Xuemei et al. Study on indepth profile control and flooding of pore-scale elastic microspheres under heterogeneous condition. *PGRE*, 2012, 19(5): 61-64.

Abstract: Due to the particularity of design principle for pore-scale elastic microspheres profile control and flooding technology, the particle-pore size matching factor was introduced and through heterogeneous parallel sandpack experiments, the plugging property of elastic microspheres under different particle-pore size matching relationship and the effect of permeability ratio on the ability of profile improvement were studied. Based on this, field test of pore-scale elastic microspheres under heterogeneous condition was carried out. Indoor experimental results show that in a better particle-pore size matching factor range, the residual resistance factor and plugging rate of sandpacks are the maximum as well as plugging effect; elastic microspheres can prefer to plug high permeability layer selectively so as to make the diversion rate of high and low permeability tube all tend to 50%, which indicates that elastic microspheres have significant selectivity on permeability; permeability ratio has an important effect on profile control an flooding performance of elastic microspheres and under condition of better particle-pore size matching factor range and lower permeability ratio, the profile improvement of elastic microspheres is better. Field test results show that when the particle-pore size matching factor is 1.52 and the permeability ratio is 3.1, the elastic microspheres can control the water injection profile effectively and the profile improve ability of target layer 65 and 67 is up to 98%; it is scientific to guide the field test of elastic microspheres profile control and flooding using particle-pore size matching factor and permeability ratio.

Key words: heterogeneous; elastic microspheres; particle-pore size matching factor; sealing property; permeability ratio; field test

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Yang Shuai, Dai Caili, Zhang Jian et al. Influence of polymer residue property on EOR after polymer injection for offshore oilfield. *PGRE*, 2012, 19(5): 65-68.

Abstract: As the hydrophobically associating polymer in Bohai Suizhong 36-1 reservoir has the character of high degree of hydrolysis and low intrinsic viscosity, laboratory has carried out the residual-recycled experiments to investigate the sealing characteristics with the changes in degree of hydrolysis and intrinsic viscosity. Residual resistance factor and recovery appreciation are determined by the physical simulation method, to study the effect of formation sealing performance and recovery evaluation by the change of polymer degree of hydrolysis and intrinsic viscosity. The results of laboratory experiments indicates that the sealing characteristics of the interacted production which originates from the reaction of residual polymer with high degree of hydrolysis and low intrinsic viscosity and recycled agent is much better than the single polymer with the residual resistance factor reaching more than 20, which lowers the intrinsic viscosity, that is, the higher the degree of hydrolysis, the better the sealing performance. The enhanced oil recovery experiments also indicate that the method can improve the recovery by 9.4%. The result of visualized simulation experiment also validates the viewpoint.

Key words: residual polymer; intrinsic viscosity; degree of hydrolysis; reutilization; enhance oil recovery

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Li Caifeng, Guo Liaoyuan, Cao Gongze et al. Research and field application of activator formulas to endogenous microorganism, Gudao Zhongyi Ng3 block. *PGRE*, 2012, 19(5): 69-71.

Abstract: The activation of Zhongyi Ng3 of Gudao after polymer flooding by means of different activator formulas is studied herein. Screening results reveal that the optimal composition of the activator formula is as follows (g/L): glucose 4, peptone 0.4, yeast extract 0.2, NH_4NO_3 0.4, $(NH_4)_2PO_4$ 0.2. The detailed results show that, at 65 ℃ and 10 MPa the endogenous microorganism can be activated evidently to 1.48×10^9 cfu/mL via the activator formula consisted of glucose and yeast extract powder. Simultaneously, the concentration of acetic acid is increased distinctly about 600 mg/L and the surface tension of water is reduced to 33.2 mN/m. Physical simulation experiment shows that the endogenous microorganism can enhance the oil recovery by 6.4 percent with the activator formula. Field test shows that the amount of this activator formula to Zhongyi Ng3 block is 405 t by the end of June 2011, and the cumulative oil yield increases by 1.0×10^4 t.

Key words: endogenous microorganism; stimulation agent; physical simulation; nutrient system; Gudao oilfield

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Luo Qiang, Wu Yongfeng, Li Dongwen et al. Steam stimulation with air by low-temperature oxidation at presence of additives. *PGRE*, 2012, 19(5): 72-74.

Abstract: The objective of this study is to investigate parameters for low-temperature oxidation of heavy oil on the volume fraction of