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水驱油藏特高含水阶段提高采收率可行性研究及技术对策

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摘要:常规砂岩油田注水开发最终采收率多为35%~50%。基于大量室内实验、应用实例和中外油田案例类比,分析了特高含水开发阶段进一步提高水驱油藏驱油效率的可行性。讨论了水驱油藏在周期注水、关停老井侧钻、多油层逐层上返或沿断层面钻加密井等扩大注水波及体积基础上,长期高孔隙体积倍数注水、低矿化度水驱等经济可行的提高驱油效率思路和方法。室内研究和矿场实践结果表明,长期注水开发砂岩油藏润湿性由偏亲油性向偏亲水性转化,残余油饱和度降低,有利于提高驱油效率。依据成熟开发油田大量类比实例,在油层和流体性质较为有利的条件下,强天然水驱油藏依靠天然能量开采,或弱天然能量油藏通过注水开发最终采收率可达70%。采用自流水注水、低矿化度水驱、同井注采工艺等技术已证实是经济可行的。特高含水开发阶段老油田已有的大量开发井和配套设施为进一步提高采收率提供了基础。应用经济可行的长期高孔隙体积倍数注水思路有望将水驱开发油田采收率进一步提高至50%~70%。

关键词:水驱开发;特高含水阶段;驱油效率;提高采收率;自流水注水;同井注采;低矿化度水驱

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Feasibility and technologies for improving recovery at extra-high water cut development stage in waterflooding reservoirs

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Abstract: The ultimate recovery of the conventional waterflooding sandstone reservoir ranges from 35% to 50%. This paper illustrates the feasibility of further improving the displacement efficiency of waterflooding reservoirs at the extra-high water cut development stage based on previous laboratory experiments, field applications, and global oilfield development cases. The economically feasible ideas and methods including long-term and large pore volume (PV) waterflooding and low salinity waterflooding etc. for improving the displacement efficiency are discussed in waterflooding reservoirs after improving sweep efficiency measures, such as the cyclic waterflooding, shut-in old well sidetracking, upward and layered waterflooding in multiple layers, or new infill wells along fault planes. Laboratory experiments and field applications reveal that the wettability of sandstone reservoirs changes from the oil-wet to the water-wet, and the saturation of residual oil reduces after long-term waterflooding, which can improve the displacement efficiency. Mature oilfield development cases indicate that with favorable reservoir and fluid properties, the ultimate recovery can reach 70% when reservoirs with strong natural waterflooding are developed by natural energy, or that with weak natural energy are developed by waterflooding. It has been proven that technologies such as dump flooding, low salinity waterflooding, and injecting and producing through one well are economically feasible. A large number of developed wells and existing facilities in mature field provide a basis for improving the recovery at the extra-high water cut development stage. The application of long-term and large PV waterflooding that is economically feasible is expected to increase the ultimate recovery to 50%-70%.

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Key words: waterflooding development; extra-high water cut stage; displacement efficiency; oil recovery improvement; dump flooding; injecting and producing through one well; low salinity waterflooding

目前中外主要中高渗透常规砂岩油田均已进入成熟开发阶段,含水率多大于90%,可采储量采出程度大于80%[1-5]。世界上最著名的几个砂岩油田如东德克萨斯油田、大庆喇萨杏油田和罗马仕金油田的可采储量采出程度分别为97.5%,92.7%和77.7%,其中东德克萨斯油田含水率大于99%,大庆喇萨杏油田含水率达94.6%[5-6]。

中外636个常规砂岩油藏天然能量一次采收率和最终采收率统计分布中值分别为15%和38.1%[7]。而以水驱开发为主要提高采收率方法的477个常规砂岩油藏(渗透率大于50 mD,原油黏度小于50 mPa·s)最终采收率统计分布中值为43.4%,比笼统统计分析结果的38.1%高出5.3%[7],更实际反映了常规砂岩油藏水驱开发的最终采收率状况。中国有研究结果给出含水率大于80%的高含水油田采出程度为33.47%,最终采收率为41%,部分油田达到45%以上[1,8]。统计结果表明,常规砂岩油田注水开发最终采收率多为35%~50%。特高含水阶段高油水比条件下产出液的处理费用大幅度上升,大量生产井被迫关井停产是油田开发面临的主要挑战。与国外油田相比,中国众多的老油田产层为多层砂岩,非均质性更强且原油性质相对较差,进一步提高水驱采收率的难度更大。

常规提高采收率的方法包括2方面:①通过改善油藏管理,优化井网和分层注水,利用加密井、水平井等措施和技术扩大波及体积提高最终采收率[7-15]。②利用强化采油(EOR)方法进一步扩大波及体积和提高驱油效率[16-18]。但EOR方法需较大投入,在低油价条件下很难获得经济效益。大量研究表明,注水开发过程中润湿性的变化有助于改善最终采收率,长期水驱可起到既扩大波及体积又提高驱油效率的双重作用[2-3,18-20]。为此,笔者深入分析成熟开发油田进入特高含水和极限含水阶段进一步改善注水开发效果提高采收率的可行性,并提出技术对策。

1 可行性分析

水驱开发是最为成熟、经济有效且应用最为广泛的以保持油藏压力为主要目标的二次采油方法。室内实验及成熟开发油田实践表明,特高含水阶段采油给油田开发带来了挑战,同时长期注水冲刷导致油藏条件变化也在一定程度上为进一步提高采收率带来了机遇,在含水率大于98%的条件下高孔隙体积倍数注水可提高驱油效率。根据油藏具体条件,通过水驱开发进一步提高最终采收率达到50%~70%具有可行性。

1.1 室内实验分析

1.1.1 润湿性改变

高孔隙体积倍数水驱实验和注水开发晚期的取心资料表明长期注水导致储层孔隙结构发生变化。具体表现在岩石表面的黏土矿物变少,大孔隙比例增多,孔隙度、渗透率增加,而这些变化在中高渗透储层和河道砂岩中的表现更为突出[19-21]。储层岩石经大量注入水冲刷后,原来具亲油特征的表面特性逐渐转变为偏亲水性。

大庆油田长垣北部萨葡油层原始储层岩石为偏亲油性,经长期水驱,最终含水饱和度为60%~99%的岩样全部转化为偏亲水性。亲水性增强,有利于进一步提高驱油效率[19-20]。与早期评价结果相比较,大庆喇萨杏油田水驱最终采收率提高约为5%~10%[1,11]。

1.1.2 驱油效率提高

驱油效率是指在油水流度比一定,均质油藏条件下的极限采收率。通常认为理论驱油效率为50%~61.6%[8]。已有室内实验探讨高孔隙体积倍数注水条件下的驱油效率[2-3,18,21-25],尽管最终结果不完全一致,但总体上认为残余油饱和度降低,可提高驱油效率达70%以上。

大庆油田利用天然岩心开展高孔隙体积倍数注水驱油室内实验[2,21,24],注水量在10 000 PV以上时,岩心一直出油[18]。14块岩心最终含水饱和度平均为86%,最高达99.2%,残余油饱和度平均为16.6%,最低为9.6%。驱油效率平均为82.9%,最高达99.1%。

孤岛、埕东、胜坨油田5口密闭取心井的1 186块样品的驱油效率统计结果表明:在特高含水阶段,134块样品的驱油效率超过70%,剩余油饱和度为16.4%,其中有4块样品驱油效率甚至超过90%,剩余油饱和度为3.9%[25]。根据大庆油田密闭取心分析结果,PⅠ1-3油层强水洗段驱油效率平均为67.3%,最高驱油效率可达90%[26]。

1.2 实例应用分析

大庆油田在511井组SⅡ7+8油层开展75 m井

距条件下的高孔隙体积倍数注水采油现场试验[21,24]。中心井511井试验开始和结束时的含水率分别为98.9%和99.2%。试验期间，注入孔隙体积倍数增加4.2倍，采出程度提高7.3%。胜利油田在孤东七区西开展$Ng5^{2+3}$油层小井距的注水开发试验[27]，注入量由1.8 PV增加到5.1 PV，含水率由98%增加到98.5%，而采出程度则大幅度增加了8.7个百分点。

上述试验说明在含水率达98%后，通过强化注水和采液仍可进一步提高最终采收率。研究者指出石油工业上通常把含水率为95%或98%时的采收率作为最终采收率，在大庆511井组小井距试验中，换油率为86 m^3/t，这在经济上是合理的，因此经济含水界限应该如何确定须重新研究[24]。

大庆油田小井距试验证实达到极限含水阶段后通过高孔隙体积倍数注水可进一步提高采收率，技术上是可行的。高孔隙体积倍数注水采油阶段注入水利用率较低，大庆511井组小井距试验每采出1%石油地质储量需注入0.6 PV的水，必须寻求经济有效的注水方式。

中外477个常规砂岩油藏的最终采收率平均为43.7%，其中30%的油藏最终采收率大于50%，3%的油藏最终采收率接近或大于70%（图1）。在最终采收率大于70%的油藏中，既有相对均质的滨岸砂坝储层，也有非均质性相对较强的曲流河、辫状河砂岩储层。而在最终采收率大于50%的油藏中，57%的油藏主要驱动类型为溶解气驱或弱天然水驱，采用人工注水开发提高采收率为20%～46%。43%的油藏以强边底水驱驱动能量为主，天然能量开发最终采收率也可达50%～70%以上（图2）。

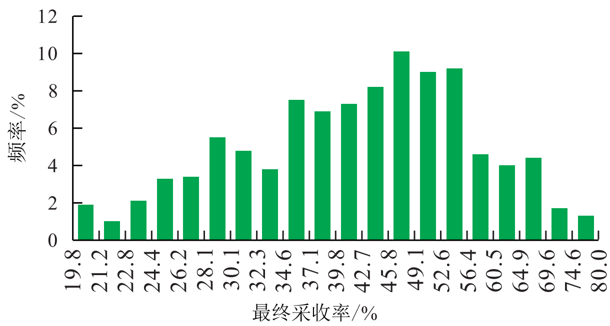

图1　477个常规砂岩油藏最终采收率分布

Fig.1　Ultimate recovery distribution of 477 conventional sandstone reservoirs

著名的东德克萨斯油田预期最终采收率为78.4%[3]。2006年以来一直在含水率大于98%的极限含水条件下产油，2009年含水率达99.1%，到2020年底，石油地质储量采出程度已达78%（图3）。

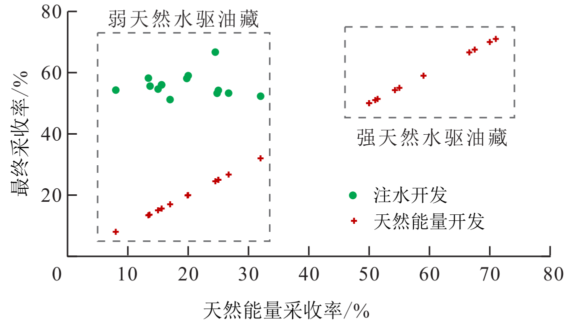

图2　注水开发油藏天然能量采收率与最终采收率交会图（最终采收率大于50%的常规砂岩油藏）

Fig.2　Primary recovery versus ultimate recovery of waterflooding reservoirs（reservoirs with ultimate recovery greater than 50%）

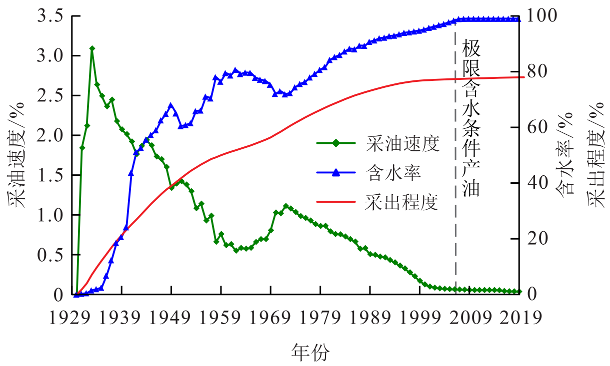

图3　东德克萨斯油田开发历史曲线

Fig.3　East Texas Oil Field development history

东德克萨斯油田开发过程中受商业利益驱动采用几十米的小井距开采，客观上扩大了波及体积。在高渗透、储层连通状况好且相对均质、原油黏度低等有利的储层和流体性质条件下，且与露头相连、地表水可连续补充的强天然水驱，辅之边缘注水，可形成长期高孔隙体积倍数注水采油，使得最终采收率高达近80%[5,28-29]。如果按波及体积系数为0.9计算，到2020年，驱油效率已达87.7%。该大型整装油田的实例充分说明，长期高孔隙体积倍数水驱可以达到远高于常规认识的驱油效率，到达极限含水阶段时，采用经济有效的实用技术仍可继续提高采收率。

综上所述，长期高孔隙体积倍数注水可以提高采收率，但现有技术、经济条件长期注水难以获得经济效益，一些油田或断块在进入特高或极限含水阶段只能关停或废弃。急需一些经济可行的技术使关停老井重新注水采油，延长油田开采周期，从而提高采收率。

2　技术对策

应用适合具体油藏特征的低成本、有效技术提

高特高含水期水驱最终采收率的主要途径包括:①以单砂体为单元的注采开发,减缓层间和平面非均质性的影响,最大程度地扩大水驱波及体积。②实现长期高孔隙体积倍数注水,延长油田开发生命期,进一步提高驱替效率。

2.1　扩大波及体积

储层的非均质性特别是侧向连通性是影响注水波及体积的关键因素。三角洲沉积砂岩储层在井距为200 m条件下井间仍分布未钻遇的孤立分流河道砂体。断层遮挡、层间渗透率差异、单一砂层平面岩性、物性变差等因素均可形成注水未完全波及的剩余油富集区。目前中国广泛应用调剖、分层注水等是挖潜剩余油的有效技术[30-33]。进一步扩大波及体积的油藏管理技术和措施主要包括:①通过周期注水,即脉冲注水、改变液流方向等方式提高水驱波及体积。周期注水可提高产量10%,降低含水率20%[34-35]。著名的罗马仕金油田预测的最终采收率为60%,油田进入成熟开发阶段采用控水、周期注水、控制采油速度等措施。1986年以来含水率为84%~86%,目前石油地质储量采出程度已达47.6%。②进一步缩小单砂体的生产和注水井距。以大庆油田为代表的多层非均质油田单层系井距多超过200 m,但进入特高含水和极限含水阶段地面的各类井的综合井距已远小于200 m。因此可以利用几十米的近井距生产井并结合可行的完井工艺逐层上返开采物性相近的储层段或厚层单砂体,最大程度提高水驱波及体积。在中国石油印度尼西亚某油田提高采收率实践中,针对纵向非均质性强、油层多的特点,采用双油管、多封隔器与滑套组合完井(图4)。应用单井接替开采不同物性的油层,使常规开采无经济效益的油层得以有效开发[36]。③利用大量关停老井的上部管柱侧钻降低钻井费用开采井间孤立砂体或分流线部位的剩余油。密井网测井信息揭示的三角洲前缘分流河道砂体形态表明,在井距为126~215 m条件下井间仍有大量的窄分流河道砂体未被钻遇[2]。目前基于三维地震、测井信息及沉积学分析的储层综合表征技术已可以揭示这些砂体的井间分布。在特高含水阶段,对关、停老井实施侧钻,可以充分利用已钻井的上部井筒及油田生产设备来控制成本,达到经济有效挖潜井间剩余油的目的(图5)。④靠近断层高含油饱和度部位平行断层面钻新井。针对钻遇的多层砂岩储层,可以采用智能完井技术实现不动管柱可选的单一层段接替或所有砂体混合开采。巴西某油田产层为复杂断块、复杂油水分布的三角洲沉积砂岩油藏,包含100多个油层[37]。实施沿断层面钻加密井43口,日产油量由350 m³/d增至1 100 m³/d,累积产量占该油田的15%,实现了二次开发(图6)。

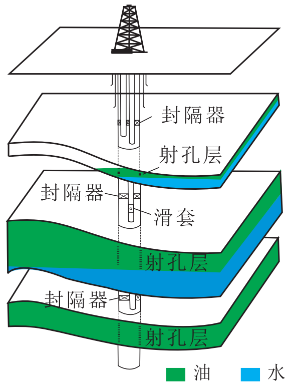

图4　双油管和多封隔器完井示意

Fig.4　Schematic diagram of completion with dual tubings and multi-packers

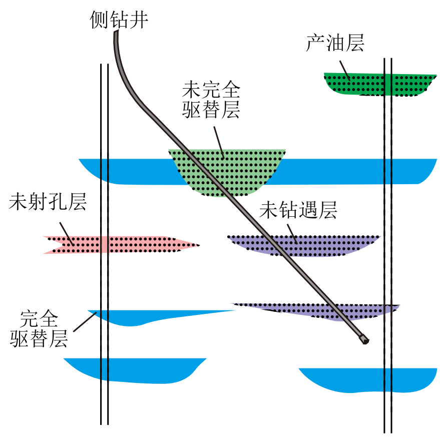

图5　三角洲前缘分流河道砂体井间老井侧钻挖潜示意

Fig.5　Schematic diagram showing poorly swept inter-well delta distributary channel sands and producing through old well sidetracking

2.2　提高驱油效率

2.2.1　自流水注水技术

自流水注水技术是指在油藏顶部或者底部存在大型水体时,利用水层的重力及与油层之间的压差,将独立的高压水层中的地层水源注入开发目的层位,以提高地层压力驱动原油的一种开采方式。与传统的注水开发方式相比,具有成本低,工艺简单,无需地面设备、注水管线等特点。该技术已应用于中东、北美和亚太一些国家的油田[38-42]。马来西亚国家石油公司尝试在开发晚期高含水阶段采用自流水注水提高最终采收率。中国平湖油田、惠州25-3油田曾开展了自流水注入现场试验研究[43-44]。诸多学者对于自流水的注水量、注水速度、技术政策界限、相关油藏的可行性等方面进行了研

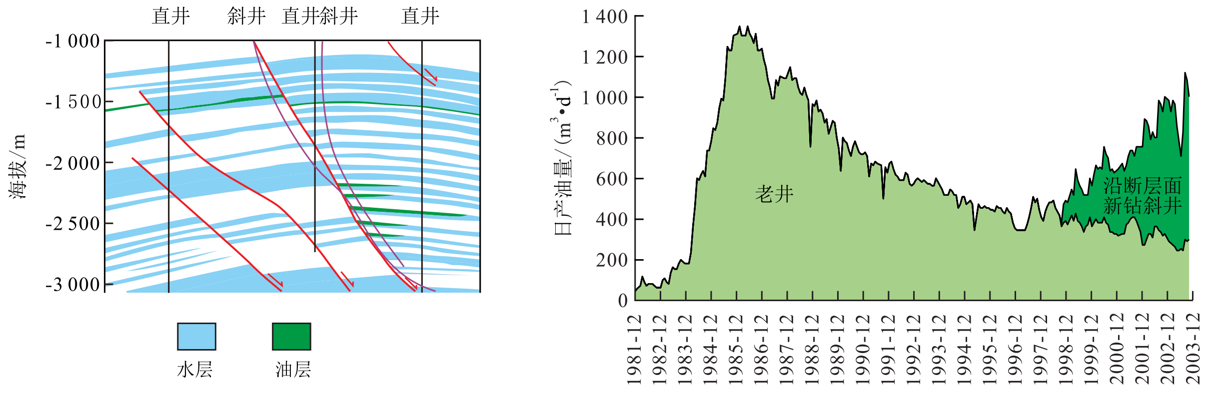

图6 巴西某油田沿断层面钻井剖面及钻井前后日产油量变化(据文献[37]修改)

Fig.6 Drilling profile along fault planes and daily oil production change of an oilfield in Brazil(Modified from Reference[37])

究[45-47]。

自流水注水技术是一种经济有效的保持油藏压力二次采油方法,既可以应用于复杂断块油田的局部注水补充能量,也可以应用于油田开发晚期极限含水阶段高孔隙体积倍数注入驱替采油。印度尼西亚某油田对断块油藏衰竭停产的老井实施自流水注水(图7),1 a后,对应的停产油井开始产油,产量逐渐增加,日产油量由初期的8 m^3/d增至95 m^3/d,提高采收率为8%。

2.2.2 低矿化度水驱技术

室内实验和现场应用已证实低矿化度水驱技术可以提高采收率,该技术又被业界称为先进水驱油技术[19,48-54]。多数研究认为其机理类似于碱水驱,即生成表面活性剂,改变润湿性,降低表面张力,同时剥离泥质颗粒也有所贡献。阿拉斯加库珀茹克油藏单井化学示踪剂测试结果证实高矿化度水驱后的残余油饱和度为39%~43%,应用低矿化度水驱后,残余油饱和度降低了9%~17%[48]。试验结果同时揭示出提高采收率程度与高岭石含量呈正相关。高岭石含量由7.6%增至14%,采收率由9%提高到17%。

BP公司在阿拉斯加北坡恩迪科特油田的低矿化度水驱现场试验提高采收率10%以上。试验过程中首先采用高矿化度水驱建立含水基线,实施低矿化度水驱三个月后对应生产井开始见效,表现为产量上升,含水率由95%降低到92%(图8)。

低矿化度水驱技术具有易于应用、低成本、有助于改善注入能力减少结垢等优点,也无需地面处理、注入液配制和操作的特殊设施,可应用于特高含水采油阶段进一步提高采收率。

2.2.3 同井注采技术

近年来井下油水分离装置研究取得了长足进展并进一步实现了同井注采,从而大幅度降低了水驱开发成本[55-58]。同井注采是在同一口井上实现注水与采油一体化的开发技术,在井筒内将高含水率采出液油水分离,分离出的水回注到油层而将分离后的低含水率采出液采到地面,由此大大地降低了注入和采出液处理费用。

同井注采技术在中国最初应用于海上油田高含水油井,主要解决举升和集输能耗高等问题。该技术在大庆油田的应用已实现含水率为99.9%产出液的油井开采,通过井下油水分离和注入,产出液

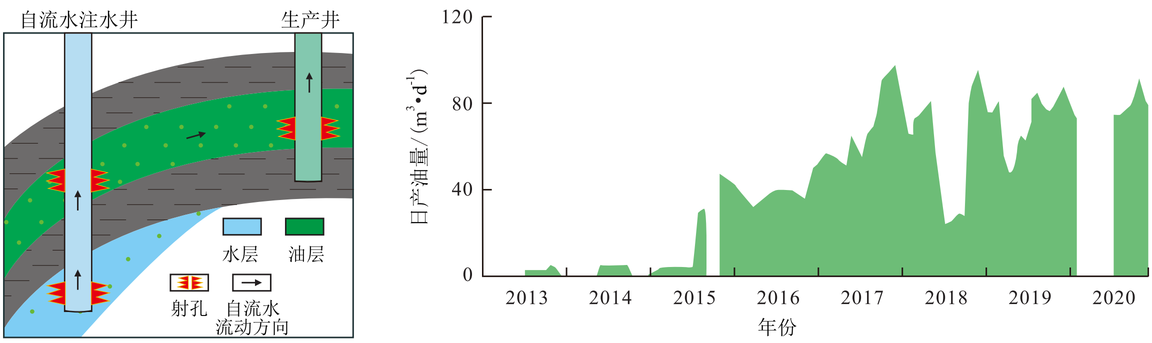

图7 停产油井注自流水剖面及恢复生产后日产油量(据文献[42]修改)

Fig.7 Dump flooding profile and daily oil production of a depleted well after recovery(Modified from Reference[42])

含水率降低为80%,大幅度减少了地面产出液油水分离与处理过程费用,从而延长了采油井经济有效的开采年限,预计可提高采收率为14%~20%[18]。

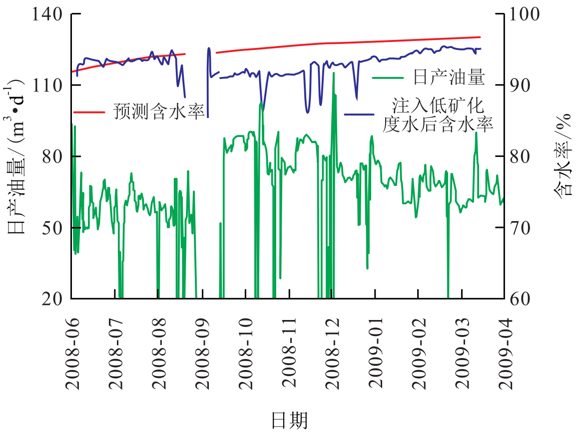

图8　恩迪科特油田低矿化度水驱现场试验产油量及含水率曲线(据文献[49]修改)

Fig.8　Production and water cut performance of Endicott Field under low salinity waterflooding test (Modified from Reference[49])

3　结论

大量研究和应用实例证明长期高孔隙体积倍数注水既可以扩大波及体积也可以提高驱油效率。长期高孔隙体积倍数注水可使驱油效率达70%以上。大量油田类比实例说明强水驱开发油藏利用天然水驱能量开采最终采收率可达50%~70%,而对于溶解气驱或弱天然水驱为主的油藏,注水可以提高采收率为20%~46%,同样取得高达70%的最终采收率。特高含水和极限含水阶段通过高孔隙体积倍数注水驱油具有技术可行性,但受经济效益的制约。进入特高含水开发阶段的成熟开发油田具有大量的近井距开发井和完善的生产设施,以此为基础,在应用周期注水、关停老井侧钻、沿断层面高含油饱和度区钻加密井等技术进一步扩大水驱开发波及体积的基础上,应用自流水注水、低矿化度水驱、同井注采工艺技术可有效降低注入、产出水处理费用和其他设施成本,提高最终采收率。另外,针对不同规模、开采经济界限的特定油藏,其应用可行性还需进一步深入研究。

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