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缝洞型碳酸盐岩凝析气藏注水开发物理模拟研究

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摘要:与一般砂岩凝析气藏不同,缝洞型碳酸盐岩凝析气藏发育有大小不同、形状各异的裂缝和孔洞,使其具有非均质性强,流体流动规律复杂等特征。如何提高该类气藏的采收率是值得研究的问题。技术成熟的注水技术具有开发成本低、水气流度比好、水驱波及效率高等优点。以塔中 86 井为例,采用露头碳酸盐岩经过人工技术制成全直径缝洞型岩心,在原始地层条件下(140.6 ℃,58 MPa)完成注水开发物理模拟实验。结果表明,采用注水保压方式开发高含凝析油的缝洞型碳酸盐岩凝析气藏效果较好;凝析油的采收率受缝洞连通方式、缝洞充填与否、压力保持水平等因素的影响。

关键词:缝洞型碳酸盐岩;凝析气藏;高含凝析油;注水;高温高压;全直径岩心;物理模拟

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Physical simulation of exploiting fractured-vuggy carbonate gas condensate reservoirs by water injection

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Abstract: Due to the development of fissures and cavities with different sizes and shapes, fractured-vuggy carbonate gas condensate reservoirs are distinct from the general sand gas condensate reservoirs, hence are characterized by strong heterogeneity and complicated flow regularity. To these reservoirs, it is a question of concern that which developing strategy is benefit to maximize the recoveries of oil and gas. As a mature technology, water injection possesses advantages such as lower cost, better gas-water mobility ratio, and higher sweep efficiency. Taking well TZ86 as a target, we accomplished a physical simulation research under initial reservoir conditions (140.6 ℃,58 MPa) by using an artificial fractured-vuggy full-diameter core which was made from an outcrop of carbonate rock. The experimental results show that the effectiveness of exploiting fractured-vuggy carbonate gas condensate reservoirs by water injection is significant. The factors such as the connectivity pattern between fissure and cavern, the pressure maintenance level of water injection, and cavern whether or not filling have effects on the recovery of condensate oil.

Key words: fractured-vuggy carbonate rock; gas condensate reservoir; high content of condensate oil; water injection; high temperature and high pressure; full-diameter core; physical simulation

缝洞型碳酸盐岩凝析气藏是经多期构造运动与古岩溶共同作用形成的一种特殊类型的气藏,其储集空间以缝洞和裂缝—孔洞为主,具有构造复杂、储层非均质性强、双孔隙网络及渗流规律复杂等特征,是当前最复杂特殊的气藏之一。如何提高缝洞型碳酸盐岩凝析气藏(尤其高含凝析油时)的采收率是一个值得研究的问题。注水作为一项成熟的技术,具有开发成本低、水气流度比好、水驱波及效率高等优点,国内外诸多学者针对注水开发砂岩凝析气藏[1-9]及缝洞型碳酸盐岩油藏[10-25]做过一系列研究,但未涉及到高含凝析油的缝洞型碳酸盐岩凝析气藏。故本文以塔中 86 井(凝析油含量 533 g/m^3,地层温度 140.6 ℃,地层压力 58 MPa,露点压力 55.4 MPa,最大反凝析液量压力 31 MPa)为例设计并完成了缝洞型碳酸盐岩凝析气藏注水开发物理模拟实验。本次研究填补了这方面的空白,取得的研究成果对于缝洞型碳酸盐岩凝析气藏的高效开发具有一定的指导意义。

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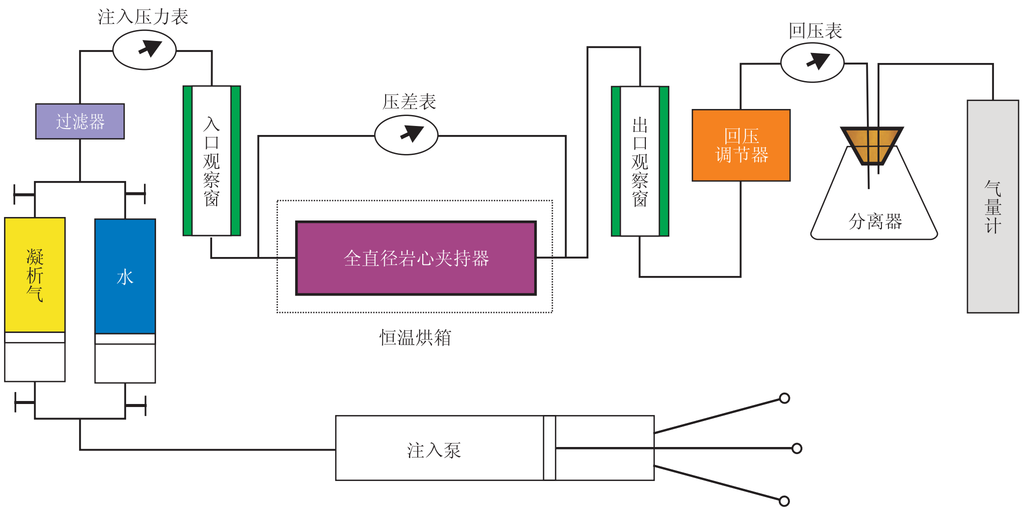

图 1　全直径岩心实验流程

Fig.1　Flow diagram of full-diameter core test

1　实验条件

1.1　实验装置

本次实验在高温高压全直径岩心驱替装置上完成,实验流程如图 1 所示。

1.2　岩心制备

由于缝洞型储层的重点研究对象是缝和洞,对基质要求较低,且实际取得的全直径岩心通常不具有缝洞代表性,达不到实验要求,故采用野外取来的碳酸盐岩露头按文献[26]中的方法制作缝洞型岩心。首先选择一块边长 30 cm 左右的方块碳酸盐岩岩心,进行人造自然单缝,使缝面大致平行于方块的任意一条棱且贯穿整块岩心;然后用直径为 4 in 的钻头钻取全直径岩心,长度 10~25 cm,保持缝尽量位于全直径岩心中央;最后根据实际情况对全直径岩心内部进行造洞。本次实验研究制作的岩心如图 2 所示。

图 2　制成的缝洞型全直径岩心照片

长度:11.117 cm;直径:9.965 cm;孔隙度:16.83%;渗透率:48.26×10^{-3} μm^2

Fig.2　Photograph of artificial fractured-vuggy full-diameter core

1.3　流体制备

参照行业标准 SY/T5543—2002,按凝析油含量 533 g/m^3、地层温度 140.6 ℃、露点压力 55.4 MPa,采用现场取得的塔中 86 井的油样及气样配制凝析气。地层水根据现场分析资料在室内自行配制,总矿化度为 137 900 mg/L,水型为 $CaCl_2$ 型。

2　实验内容

基于未填砂及填砂(模拟孔洞被外来固相介质充填)的人造缝洞岩心设计了如下 9 组实验:

(1)衰竭实验 4 组(未填砂及填砂时水平衰竭、垂直衰竭各 1 组):衰竭到 10 MPa(废弃地层压力);

(2)水平水驱实验 3 组(保持露点压力注水,未填砂和填砂各 1 组;保持最大反凝析液量压力注水,岩心未填砂 1 组):岩心水平夹持,压力衰竭到露点压力(最大反凝析液量压力)时开始注水,水突破后不出油结束注水,最后衰竭到 10 MPa;

(3)垂直水驱实验 2 组(未填砂和填砂各 1 组):岩心垂直夹持,上部采气,压力衰竭到最大反凝析液量压力时开始从下部注水,水突破后不出油结束注水,最后衰竭到 10 MPa。

3　实验结果及分析

图 3 及表 1 中的数据显示:(1)注水开发时的凝析油最终采出程度远高于衰竭开发时。因为衰竭开发过程中,大量析出的凝析油滞留于孔洞底部无法采出,致使凝析油采出程度低;(2)注水开发时,绝大部分凝析油是在注水突破前采出的;(3)虽然注水开发时的凝析油采出程度整体较高,但是不同实验条件下的凝析油最终采出程度有着较大

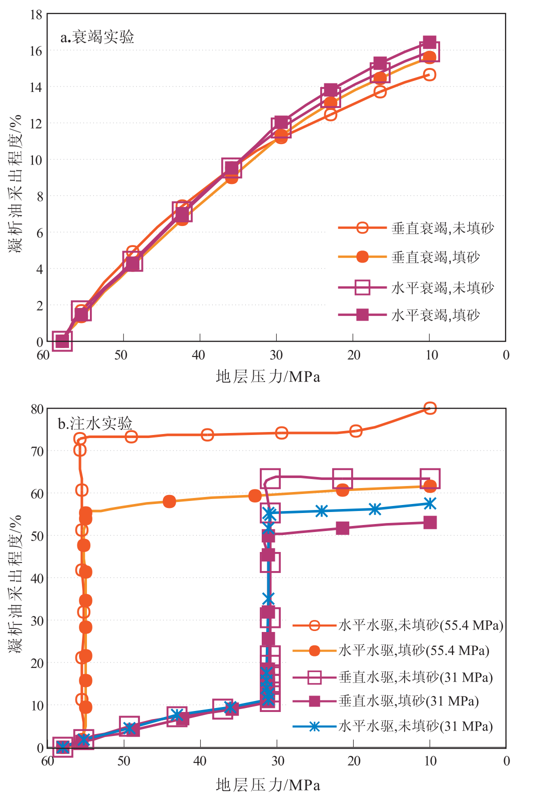

图 3　凝析油采出程度与地层压力的关系曲线

Fig.3　Variation of condensate recovery with reduced pressure

表 1　不同实验条件下的凝析油采出程度

Table 1　Condensate recovery under different experiment conditions

实验	填砂与否	岩心夹持方式	凝析油采出程度/%		
			注水前衰竭	注水保压	衰竭至10 MPa
水平衰竭	未填砂	水平			15.95
	填砂	水平			16.44
垂直衰竭	未填砂	垂直			14.64
	填砂	垂直			15.55
保持露点压力(55.4 MPa)注水	未填砂	水平	1.66	72.6	79.95
	填砂	水平	1.5	55.27	61.39
保持最大反凝析液量压力(31 MPa)注水	未填砂	水平	11.09	55.33	57.45
	未填砂	垂直	10.83	63.05	63.05
	填砂	垂直	10.99	50.04	52.99

差别。下面就注水开发缝洞型碳酸盐岩凝析气藏时影响凝析油采收率的因素做分析。

3.1　注水越早凝析油采收率越高

表 1 中数据显示，未填砂岩心水平夹持时，保持 55.4 MPa(露点压力)注水时的凝析油采出程度比保持 31 MPa(最大反凝析液量压力)注水时高 17.27%。从图 4 中可看出，保持露点压力注水过程中，无凝析油析出，注入多少水就驱替出多少体积的凝析气，生产气油比维持在原始气油比水平，凝析油采出程度与累积注水量间呈现较好的线性关系。而保持最大反凝析液量压力注水之前，反凝析出的油量达到最大值并滞留于孔洞的底部，气相中的凝析油含量减少，当液面抬升至水平缝面之前凝析油产量低，采出程度低；累积注水 0.4 HCPV 后，析出的凝析油被抬升至水平缝面后沿裂缝通道采出，产油量迅速升高，当注水突破后油气产量急剧下降直至不出油，较为复杂的油气水三相渗流使得其凝析油采收率相对较低。上述分析表明，越早注水，地层压力保持水平越高，凝析出的油量越少，凝析气中的凝析油含量就越高，最终采出程度也越高。

3.2　缝洞垂直连通时凝析油采收率相对较高

图 5 表明，保持最大反凝析液量压力注水时，岩心垂直夹持(缝洞垂直连通)时的凝析油采出程度高于水平夹持(缝洞水平连通)时，这是由于缝洞水平连通时，裂缝平面将洞分割成上(0.4 HCPV)、下(0.6 HCPV)两部分，当注入水的液面升至裂缝平面后会突破(累积注水 0.7 HCPV)，注入水只占据了缝面下部的孔洞空间，而缝面上部的洞中仍聚集有凝析气，即俗称的“阁楼气”；当缝洞垂直连通时，受重力分异作用影响，注入水在洞底部聚积，随着注水量增加，油相逐渐往洞顶移动，气相也不断被驱出，最终注入水占据了 0.9 HCPV 的缝洞空间，故其凝析油采出程度相对较高。上述分析表明，缝洞连通方式会对注水效果产生一定的影响，缝洞垂直连通时，注水突破前累积注入水量较高，水驱波及体积大，凝析油采出

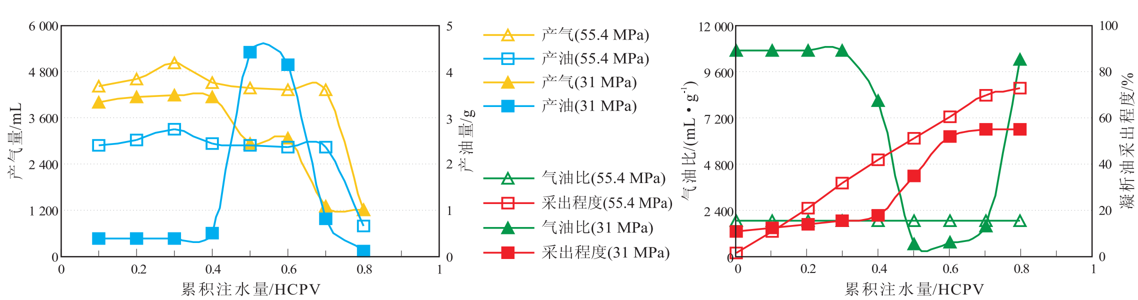

图 4　不同压力下的气油比及产量对比

岩心未填砂

Fig.4　Contrast curves of GOR and production under different pressure conditions

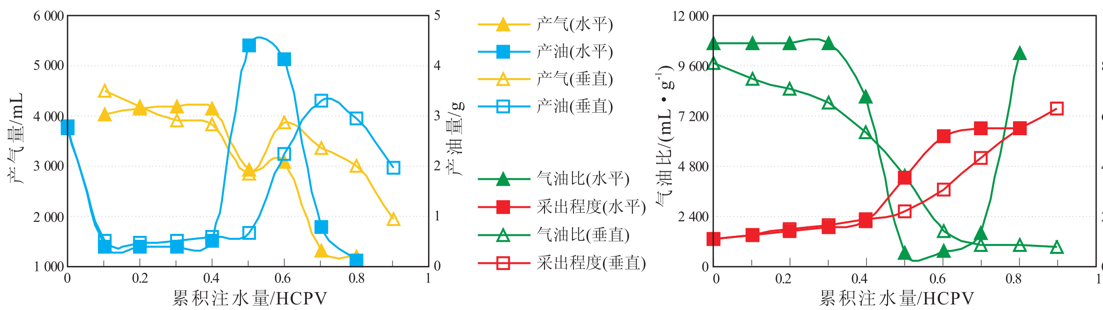

图 5　不同缝洞连通方式注水实验气油比及产量对比

Fig.5　Contrast curves of GOR and production under different connectivity pattern between fissure and cavern

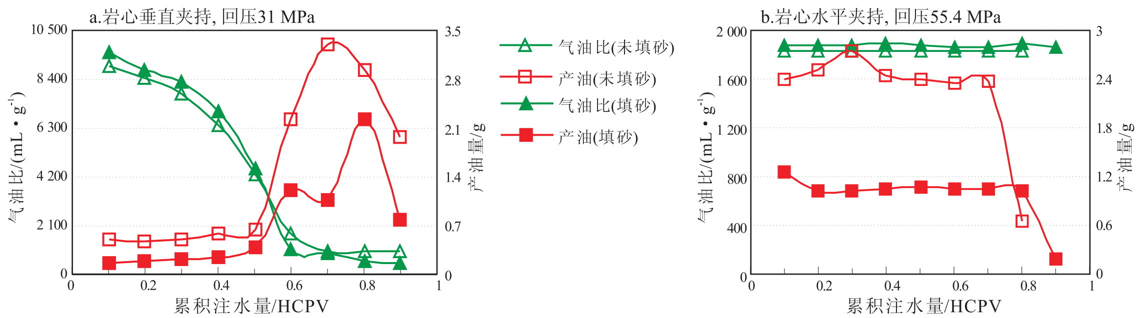

图 6　填砂与未填砂岩心注水实验对比曲线

Fig.6　Contrast curves of waterflooding experiments while core was filled and unfilled respectively

程度相对较高。

3.3　缝洞充填后凝析油采收率有所降低

从图 6 中可清晰看出,缝洞岩心填砂后各注水阶段的产油量均低于未填砂时,其凝析油采出程度也相应较低。分析认为缝洞岩心填砂后,非连续的洞变成了连续多孔介质,气、水的流体性质差异使得注入水容易在连续多孔介质中渗流,并将部分凝析气封存在孔隙中;其次,岩心填砂后表面积增大,从而增加了多相渗流阻力,所以相同注水条件下,填砂岩心的凝析油采出程度不及未填砂岩心。

4　结论

(1)与衰竭开发相比,注水开发缝洞型碳酸盐岩凝析气藏时的凝析油采出程度高、开发效果较好。

(2)缝洞垂直连通时,水驱波及体积大,凝析油采出程度相对较高。

(3)地层压力越高时注水,凝析油采收率越高。

(4)孔洞被充填时,凝析油采收率有所降低。

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