塔中Ⅰ号气田东部碳酸盐岩储层的试井特征分析

温晓红[1] 邓继学[2] 苏敏文[2] 孙贺东[3]

1. 中国地质大学(北京)能源学院 2. 中国石油川庆钻探工程公司长庆井下技术作业公司 3. 中国科学院力学研究所

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摘 要 塔里木盆地塔中Ⅰ号气田东部试验区储层高温高压,流体性质和流动机理复杂;试井曲线具有多样性、复杂性及多解性的特点,试井分析面临巨大的挑战。为此,根据研究区地质特点及有关资料录取情况,采用现代试井分析方法与生产动态分析相结合的非均质气藏动态描述综合技术,将储层划分为视均质、双重孔隙、复合模型以及裂缝、裂缝孔洞模型等 5 种类型进行试井分析。结果表明:该区储层非均质性较强,平面连通性差;试井特征与稳产能力有着紧密的联系,对不同类型的井,应制订相应的开发技术对策。

关键词 塔中Ⅰ号气田 碳酸盐岩 试井 储集层 类型 生产能力 特征 动态描述

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塔里木盆地塔中Ⅰ号气田东部试验区[1-3]已经建成 10×10^8 m^3 天然气、23×10^4 t 凝析油的生产能力。其中有生产井 32 口,除试采数据外,还有大量的试油、试井资料。通过对动态资料的分析,建立了单井动态描述方法[4-5]。单井动态描述是处理和解释气井试井、试采过程中录取到的压力、产量等动态数据响应,以现代试井分析(Pressure Transient Analysis,PTA)和生产动态分析(Production Analysis,PA 或 Rate Transient Analysis,RTA),特别是最新发展的数值试井分析方法和技术为依托,结合静态信息对气井所处地层情况进行全新解读以获取气藏或气井参数的过程。气井试井解释经验表明:将短期试井与长期生产动态相结合进行试井解释是降低多解性的有效手段之一。综合采用试井、生产分析进行单井储层动态描述[6],可准确对储层渗透率、表皮系数、水体大小、单井控制储量、可采储量等进行评价,大大降低了试井解释多解性。笔者在此基础上,将试井曲线进行分类[7-8],探索试井曲线类型与储集体的对应规律。

1 单井动态模型特征

试采井单井动态描述结果表明:单井试井曲线多样,主要有视均质模型、双重介质模型、裂缝模型、裂缝—孔洞模型、复合模型等。

1.1 视均质模型

均质地层是指均匀分布的渗流介质,视均质地层特征曲线在形态和表现形式上同均质地层一样,所不同的是流体的储渗介质有所差异,其特征是地层有一定的自然产能,关井压力恢复速度快,双对数诊断图上导数曲线具有明显的径向流段,能够反应地层内部的渗流特征,说明储层自身条件较好,措施效果也是几种曲线类型中最好的,措施成功率最高[2]。

如 TZ621 井,4 851~4 885 m 井段的储层测井解释孔隙度为 2.66%,岩性为生屑砂屑灰岩,针状溶孔及小型溶蚀孔洞发育,主要发育Ⅱ、Ⅲ类储层,储渗综合评价为孔洞型。试油期间,开井流动曲线近似一条水平直线,呈干层特征;初关井压力恢复较快,表明地层渗透性较好(图 1)。压裂后,用 4.9 mm 油嘴生产,折合日产油 103.87 m^3,折合日产气 47 320 m^3,效果显著。试井解释表现出典型的均质地层特征。由于广泛发育洞穴,且洞穴内岩石充填较少,所以此类储层的渗流条件非常好,试井解释渗透率为 270 mD,初期产能高,但稳产条件取决于洞穴的弹性空间大小以及与洞穴相连的储集体储渗能力的大小。该井自2004年

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作者简介:温晓红,女,1978 年生,工程师,博士研究生;主要从事油气藏工程方面的研究工作。地址:(065007)河北省廊坊市 44 号信箱。电话:(010)69213155。E-mail:wenxh69@petrochina.com.cn

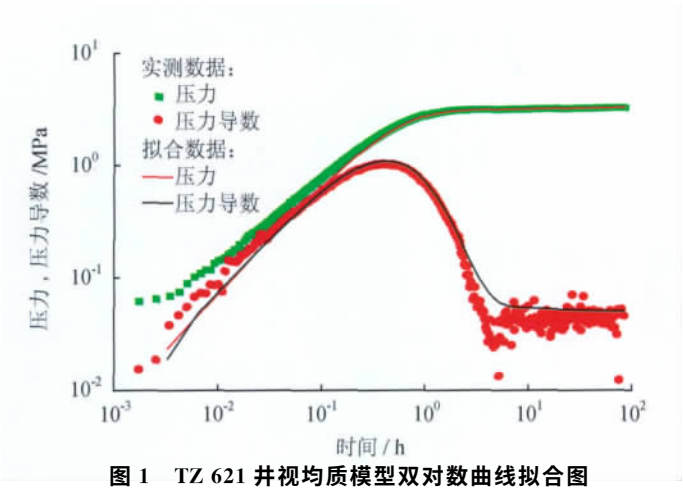

图 1　TZ 621 井视均质模型双对数曲线拟合图

12 月 8 日到 2011 年 3 月 10 日关井前，累计产油 9.9×10⁴ t，累计产气 4 400×10⁴ m³。

1.2　双重介质模型

双重孔隙介质模型是塔中碳酸盐岩储层的主要类型之一，表明尽管碳酸盐岩基质孔渗条件极差，但在有效储渗体中高导流缝洞与微细缝隙之间形成了类似双重介质流动特性的渗流介质，这一特性也说明在缝洞单元中溶孔、微细裂缝较为发育，具有一定的储集条件。

如 TZ82 井，5 430～5 487 m 井段测井解释孔隙度为 1.35%。沉积亚相为灰泥丘，微相为丘核与丘坪。在 5 430～5 450 m 井段微相为丘坪，岩性为灰白色含砂屑泥晶灰岩，大量晶洞全充填，少量半充填；5 450～5 490 m 井段微相为丘核，岩性为深灰白隐藻泥晶灰岩，下部见大量晶洞被白色方解石充填。主要发育Ⅳ类储层。试井解释模型采用双孔模型(图 2)。TZ82 井于 2005 年 9 月 17 日开始试采，2006 年 7 月底因气油比高关井，累计产油 1.7×10⁴ t，累计产气 4 016×10⁴ m³。

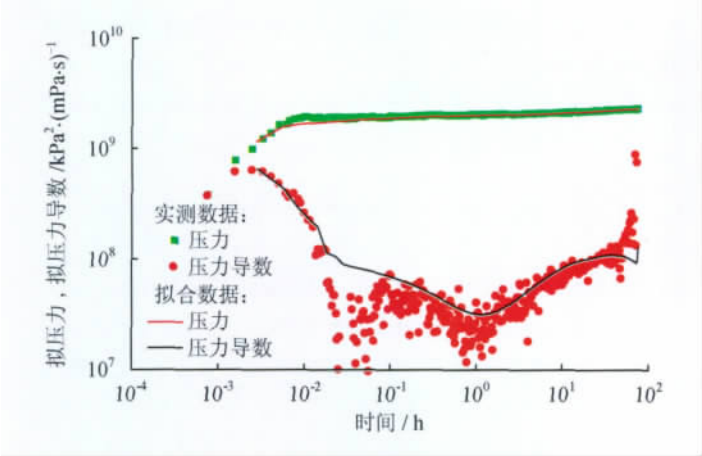

图 2　TZ82 井双重孔隙介质模型双对数曲线拟合图

1.3　裂缝模型

裂缝井模型也是塔中碳酸盐岩储层的主要类型之一，此类井由于基质孔渗条件差，能量补给不足，相应的产能低、递减快。如 TZ828 井，5 595～5 603 m 储层的沉积环境主要为粒屑滩、礁丘亚相，礁翼、中高能砂屑滩微相。岩性生屑砂屑灰岩、层孔虫骨架岩，含大量棘屑、发育溶洞、灰色生物礁灰岩、见高角度构造缝和蜂窝状溶蚀孔洞。孔隙度平均值为 1.8%，储层类型以Ⅰ、Ⅱ类为主。试油期间开井流动曲线近似一条直线，开井期间地面无产出，表明地层无自喷能力；关井压力曲线恢复缓慢，反映储层为低渗透储层。二次关井导数曲线后期出现不规则，是由于井筒相变的影响造成的，如图 3 所示，试井解释只能用 10 h 以内的数据。

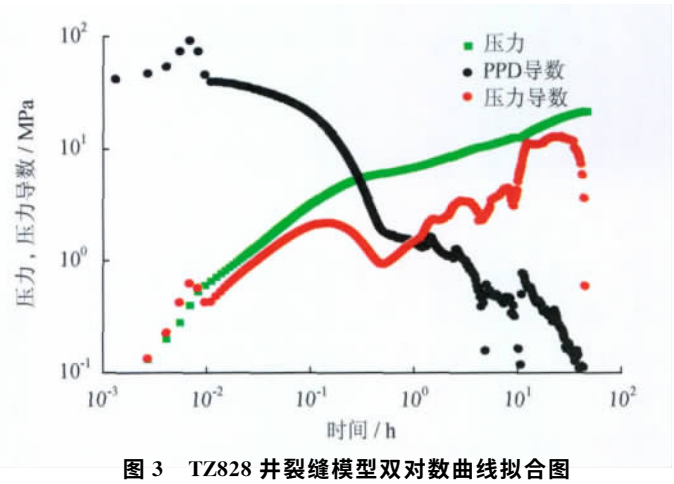

图 3　TZ828 井裂缝模型双对数曲线拟合图

该井 2008 年 6 月 8 日—8 月 10 日之间进行了短期试采，关井前累计产油 220 t，累计产气 39×10⁴ m³。油压从 7.5 MPa 降到 0。现代生产动态分析结果表明，该井控制范围有限，按照气相计算控制储量只有 70×10⁴ m³，井控半径只有 70 m。

1.4　裂缝—孔洞(串珠状)模型

裂缝—孔洞模型是塔中碳酸盐岩储层的主要类型之一。虽然基质孔渗条件差、产能低，但是由于有能量补给，该类型气井有一定的稳产期。碳酸盐岩地层的裂缝、孔、洞发育带，有时呈片状发育，在这些片状发育区域之间，被渗透性好、但极狭窄的通道连接，形成串珠状。

如 TZ62 井，4 704.5～4 753.5 m 井段储层的沉积环境主要为砂屑滩、层孔虫—海绵骨架礁，沉积微相为中高能砂砾屑滩、礁顶—礁坪、礁翼—礁核。岩性主要为浅灰色隐藻泥晶灰岩、泥亮晶生屑砂砾屑灰岩、珊瑚格架灰岩，发育溶蚀孔洞及高角度裂缝，裂缝被方解

石充填。孔隙度介于 1.84%～6.2%，Ⅰ、Ⅱ、Ⅲ类储层均有发育。该井从 2004 年 3 月 23 日开始一直进行试采，酸压改造后投产，双对数曲线显示出明显的串珠状特征(图 4)。截至 2009 年 1 月 5 日关井前，累计产油 1.4×10^4 t，累计产气 $3\ 125\times10^4$ m^3，呈现出阶梯稳产特征。

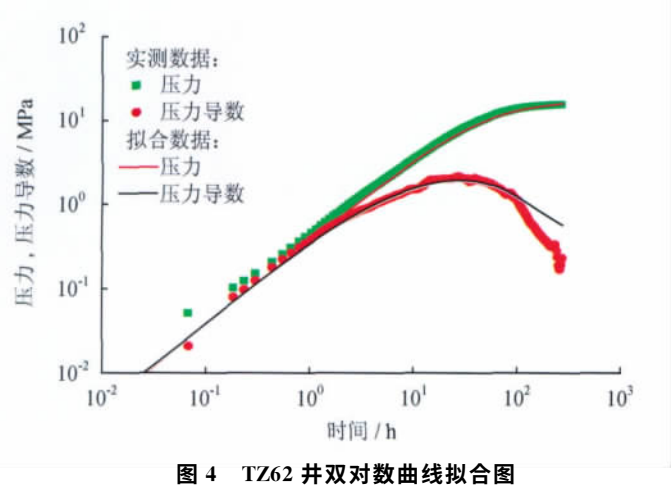

图 4 TZ62 井双对数曲线拟合图

1.5 复合模型

复合模型是塔中碳酸盐岩储层的主要类型之一，大部分井层表现为外围条件变差模型特征，内区控制范围很小，流压下降快，试采井基本无稳产期。

如 TZ83 井，5 666～5 684 m 井段储层的沉积环境主要为粒屑滩、灰泥亚相，沉积微相主要发育中等能量砂屑滩、丘核。岩性主要为隐藻泥晶灰岩，其中泥质条带被黑色和绿色泥质充填，孔隙度介于 0～3.8%，储层类型以Ⅲ类为主，夹Ⅳ类储层。完井酸压求产测试，7 mm 油嘴产量基本稳定，但是流压降低 4.0 MPa 左右，说明单井控制范围有限。试井曲线表现出外围变差的复合模型特征(图 5)。

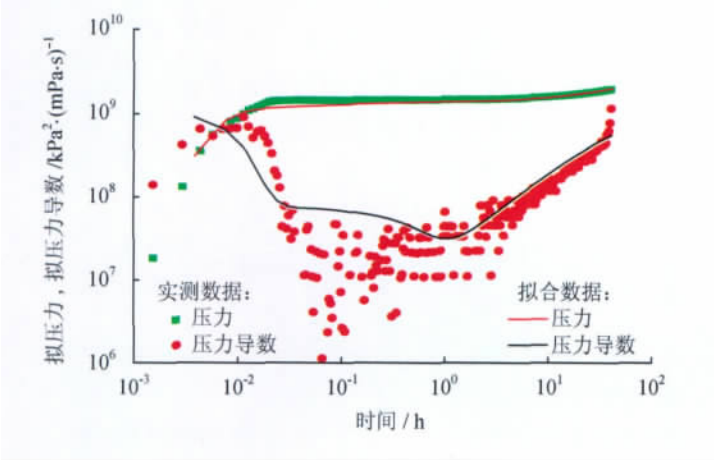

图 5 TZ83 井试井解释拟合图

2 试井与产能的关系

试采井单井动态描述结果表明试验区内试井特征多样，单井渗透率低，非均质性强，渗透率介于 0.1～130 mD，以中低渗透为主。试井特征与产能特征关系密切。对于视均质与双重孔隙介质情形来说，试采过程中产量高且稳定，递减慢；对于裂缝孔洞型情形来说，虽然产量低，但能保持稳定；对于裂缝型与外围变差的复合模型，产量递减快，压力衰竭快，基本无稳产期。

3 结论及建议

1)该区试井曲线类型多样，主要有视均质模型、双重介质模型、裂缝模型、裂缝—孔洞模型、复合模型等。储层非均质性较强，平面连通性差，局部存在连通的可能性。试井特征与稳产能力有着紧密的联系，对不同类型的井，应制订相应的开发对策。

2)试井曲线虽然类型多样，但并没有表现出所谓的“三重介质模型”特征，即双对数曲线出现 2 个下凹的情形；在实际解释过程中，应坚持“避繁就简”的原则，即用最简单的模型拟合生产历史，对气井的未来生产动态做出合理的预测，而不仅仅是为了求取几个物性参数。

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zing and acid fracturing by regular methods. In review of this, a novel surfactant-based in-situ diverting acid system is designed for acidizing high temperature formations, for which the viscosity of reacted acid is up to 150 mPa·s under the condition of 150 ℃ and 170 s^{-1}. The diverting property of this system is tested by using the HTHP rheometer, three-core parallel flow experimental instrument and NMR scanners experimental system. The results show that the injecting pressure of this in-situ self diverting acid system increases at first with the increase of injection volume. When a certain quantity of such acid is injected, the injecting pressure increases sharply and reaches a maximum of 6.3 MPa, which is 60 times the initial pressure. The injecting pressure of this self diverting acid system with notable diverting performance is 20 times that of the regular acid system. This technique has been used with good performance for acidizing and acid fracturing at 42 wells in the Tarim carbonate hydrocarbon reservoirs.

Key words: Tarim Basin, carbonate reservoir, formation, stimulation, in-situ diverting acid system, temperature, application

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Shen Jianxin, senior engineer, born in 1970, is studying for a Ph. D degree and is now engaged in stimulation of reservoirs.

Add: Kurle, Xinjiang, 841000, P. R. China

Mobile: +86-13909968172 **E-mail**: sjianxintz@sohu.com

Saltout damage resulting from weighting drilling fluid and countermeasures in the stimulation operations of HTHP gas reservoirs

Lin Qicai[1], Lin Yingzhi[2], Li Jianzhong[1]

(1. *Downhole Services Company, Chuanqing Drilling Engineering Co., Ltd., CNPC, Chengdu, Sichuan* 610051, *China*; 2. *School of Petroleum Engineering, Southwest Petroleum University, Chengdu, Sichuan* 610500, *China*)

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Abstract: Saltout damage will easily occur when the weighting drilling fluid is used in fracturing treatment for high temperature and high pressure (HTHP) reservoirs. Thus, to mitigate and prevent such damage is of great significance to enhancing the stimulation efficiency of HTHP gas reservoirs. In view of this, the simulation is made on the concentration variation of salts in the backflowing weighting fluid after frac treatment, meanwhile the backflowing fluid analysis and core flow experiments are conducted. The following results are achieved. (1) The salt concentration found in the backflowing weighting drilling fluid will be high enough to cause damage to the reservoirs, which will badly affect the stimulation result. (2) The saltout phenomenon is mainly caused by types and amount of weighting agents, temperature, pressure and velocity of backflowing fluids. (3) Saltout will easily occur near the fractured well wall or near wellbore fractures. (4) The alternative injection of the weighting frac fluid and the normal frac fluid will effectively prevent the saltout; the active water fracture closure can be used to remove the saltout damage on the formations.

Key words: high temperature and high pressure, gas reservoir, temperature, pressure, stimulation, weight liquid, saltout, formation damage

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Lin Qicai, senior engineer; born in 1962, holds an M. Sc. degree and is mainly engaged in experiments and simulation of fracturing acidification.

Add: No. 6, Ruifeng Lane, 2nd Circle Rd., Chengdu, Sichuan 610051, P. R. China

Mobile: +86-13899075159. **E-mail**: linqicai1557@sina.com

Characteristics of well tests in the carbonate reservoirs of the eastern Tazhong-1 Gas Field, Tarim Basin

Wen Xiaohong[1], Deng Jixue[2], Su Minwen[2], Sun Hedong[3]

(1. *School of Energy Resources, China University of Geosciences, Beijing* 100083, *China*; 2. *Downhole Services Company, Chuanqing Drilling Engineering Co., Ltd., CNPC, Xi'an, Shaanxi* 710018, *China*; 3. *Insti-*

tute of Mechanics, Chinese Academy of Sciences, Beijing 100190, *China*)

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Abstract: The reservoirs in the pilot test zone of the eastern Tazhong-1 Gas Field, Tarim Basin, are under high temperature and high pressure, where the properties of fluids and flowing mechanism are quite complicated. In addition, the well test curves are of multiplicity, complexity and ambiguity, so it is extremely difficult to carry out well test analysis. In view of this, based on the geological features in this study area and the related data, the integrated technology of dynamic description of heterogeneous reservoirs is adopted combined with modern well test analysis and well performance analysis, on this basis, the reservoirs are classified into five models for well test analysis, including a pseudo homogeneous model, a double porosity model, a composite model, a fracture model, and a fractured vuggy model. Results show that (1) the reservoirs in this study area have relatively strong heterogeneity and poor connectivity; (2) due to a close relationship between well testing characteristics and steady well productivity, corresponding technical measures should be made for different types of wells.

Key words: Tazhong-Ⅰ Gas Field, carbonate, well test, reservoir, type, production capacity, characteristics, dynamic description
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Wen Xiaohong, engineer, born in 1978, is studying for a Ph. D degree and is mainly engaged in the reservoir engineering.
Add: Mail Box 44, Wanzhuang, Langfang, Hebei 065007, P. R. China
Tel: +86-10-6921 3155 **E-mail**: wenxh69@petrochina.com.cn

Phase behavior of CO_2 sequestration and the enhanced natural gas recovery

Sun Yang, Du Zhimin, Sun Lei, Tang Yong, Pan Yi
(*State Key Laboratory of Oil & Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan* 610500, *China*)

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Abstract: The capture and sequestration of CO_2 can effectively reduce the amount of CO_2 in the atmosphere, but it involves a high cost. A gas reservoir within a specific range of temperature and pressure will be an ideal space for the CO_2 sequestration, which can ensure the sequestration stability of supercritical CO_2. Some researchers suggest that natural gas with development potential in the reservoir might occupy the space for supercritical CO_2, which will badly affect the stability and sequestration of CO_2. A proper sequestration depth and the application of gas displacement by CO_2 for natural gas development can favor the CO_2 sequestration and reduce costs. During the process of CO_2 injection, the natural gas displacement by CO_2 is "miscible displacement". According to the temperature and pressure conditions of the PY dry gas reservoir, and based on the laboratory test of the PVT phase behavior for the mixed CO_2 and natural gas system, this paper analyzes the changes of deviation factor of three kinds of fluid zones, especially the supercritical CO_2 gas transitional zone, as well as the changes of underground volume ratio, density and viscosity. The paper makes clear the necessity and feasibility of CO_2 sequestration in reservoirs and CO_2 injection for the improvement of gas recovery. It accordingly recommends the feasible injection depth of supercritical CO_2 and the practical gas production pressure range for enhancing the recovery of the PY gas reservoir.

Key words: gas reservoir, CO_2, sequestration, depth, phase, recovery factor, supercritical CO_2
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Sun Yang, born in 1984, is studying for a Ph. D degree. She is engaged in researches into the improvement of hydrocarbon (fluid) recovery by gas injection and CO_2 sequestration.
Add: No. 8, Xindu Avenue, Xindu District, Chengdu, Sichuan 610500, P. R. China
Mobile: +86-13880551877 **E-mail**: sakyana@126.com

Design and application of anti-fatigue sub for gas drilling

Zhu Huashu[1], Fang Zhou[1], Wang Xiyong[1], Fan Xilian[1], Tang Hongwei[1], Lian Zhanghua[2]