

开采工艺

水平压裂缝导流作用下的油藏数值模拟方法

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摘 要: 埋深浅、油层破裂压力高或 EOR 过程中垂向地应力减小的油层水力压裂后容易形成水平裂缝, 为此基于模拟垂直裂缝的嵌入裂缝模型, 提出了一种能够高效处理水平裂缝的油藏数值模拟方法, 准确模拟了水平裂缝对油层开采状况的影响。采用规则网格单独剖分油藏基质, 根据水平裂缝与油藏网格的多边形相交面划分非规则裂缝网格, 通过定义非相邻网格连接记录裂缝网格与基质网格、井之间的连接关系。基质与裂缝耦合的流体流动方程离散后, 建立了带有加边七对角稀疏系数矩阵的三维油藏基质与裂缝系统数值模拟模型。应用该模型模拟了含有水平裂缝的一注一采低渗油藏, 并与局部网格加密模型、多段井模型以及等效渗透率模型的模拟结果进行对比, 该模型的模拟结果与局部网格加密模型比较接近。最后以大注采压差两注一采水驱开发的低渗油藏为例, 研究了不同裂缝穿透比和无量纲导流能力对油井生产动态的影响。

关键词: 水平裂缝; 低渗油层; 嵌入裂缝模型; 油藏数值模拟; 裂缝穿透比; 无量纲导流能力

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埋深浅、油层破裂压力梯度大的低渗油层水力压裂后容易形成水平裂缝^[1-2], 如我国的大庆油田。另外, 采取了提高采收率增产措施的油藏, 上覆地层负荷发生改变, 当垂向地应力小于水平地应力时, 油层水力压裂后产生水平裂缝^[3], 如美国的 Belridge 油田。水平裂缝的裂缝面垂直于井筒延伸方向, 对低渗油层内的流体流动影响很大。油藏数值模拟中水平压裂缝的处理方法主要包括局部网格加密^[4]、多段井模型近似^[5]和裂缝渗透率等效^[6]等, 其中局部网格加密方法是通过在低渗基质层之间添加高渗裂缝层来表征水平裂缝, 模拟精度较高但对于裂缝条数多、走向与基质层展布方向存在夹角的情况不适用。多段井模型近似方法则是通过将基质内水平裂缝的影响转化为多段井来近似表征, 然而井筒内的管流与裂缝内的高速流动存在一定差别^[7], 模拟误差较大。裂缝渗透率等效方法则是通过增大裂缝所在基质网格的渗透率来近似模拟, 不能反映裂缝与基质间纵向上的流动, 对于密网开发的区块模拟误差比较大。为了克服这些不足, 本文基于模拟垂直裂缝的嵌入裂缝模型^[8-9]提出了水平压裂缝导

流作用下的油藏数值模拟方法, 更为准确简便的模拟了水平裂缝与基质之间的窜流, 以及水平裂缝内的向井流动过程。

一、数学模型

1. 网格剖分

采用正交结构网格划分油藏基质, 将水平裂缝处理为虚拟的非结构化网格嵌入在基质网格中。基质与裂缝的网格剖分结果及相互连接关系如图 1 所示。

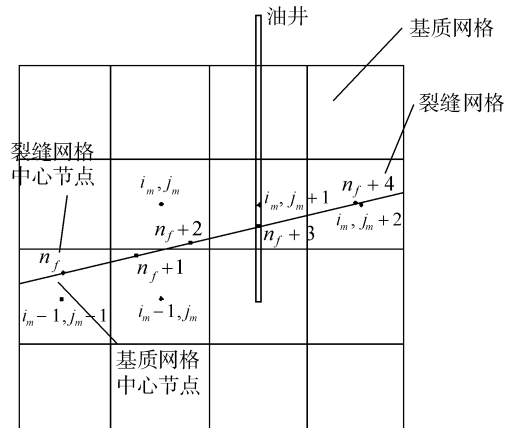


图 1 基质与裂缝的网格剖分结果示意图

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2. 非相邻网格连接

裂缝网格和基质网格的记录和编号过程相互独立,通常在油藏数值模拟模型中只有相邻网格由于压力差的存在才发生流体交换,因此需要定义非相邻网格连接(Nonneighboring connection 简称 NNC)记录裂缝网格与所在基质网格之间的联系^[8]。图 2 中 $NNC_1 \sim NNC_6$ 是根据图 1 所示的基质与裂缝网格建立的非相邻网格连接, $NNC_1 \sim NNC_5$ 是裂缝与基质之间的非相邻网格连接, NNC_6 是油井与裂缝之间的非相邻网格连接; $m_1 \sim m_{16}$ 是 16 个基质网格的编号; $f_1 \sim f_5$ 是 5 个裂缝网格编号。

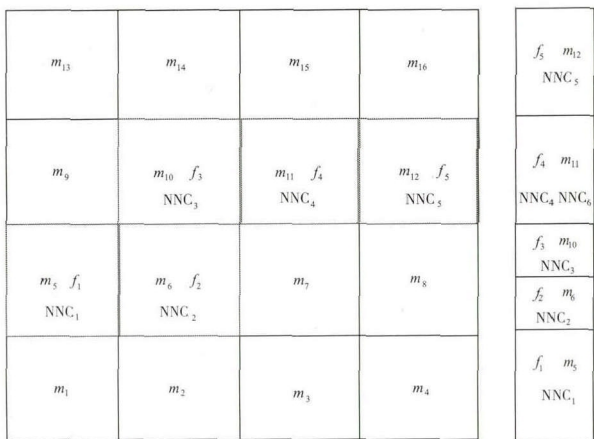


图 2 非相邻网格连接示意图

3. 数值离散方程

基质和裂缝内每个网格节点的残差方程经过全隐式离散后,每个网格的有限差分方程形成了加边七对角稀疏系数矩阵的数值模型,如图 3 所示。其中 A 为各基质网格压力的系数矩阵,与常规的三维油藏七对角矩阵相似^[10]; B 、 C 为基质网格压力与裂缝网格压力的关联系数矩阵; D 为各裂缝网格压力的系数矩阵; Δp_m 是基质网格两次迭代之间的压力差; Δp_f 是裂缝网格两次迭代之间的压力差。

在求解该数值模型时,若裂缝位于油藏内部,则

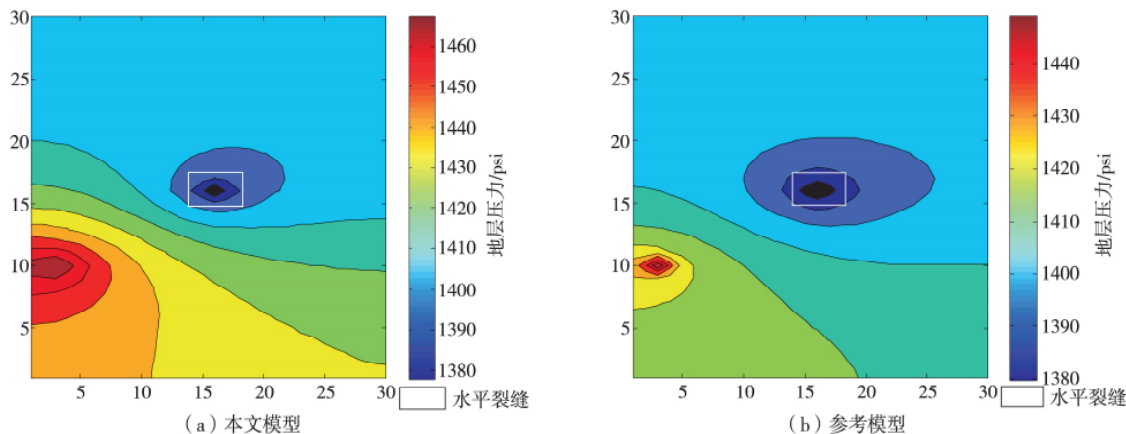


图 4 含水平裂缝油藏一注一采开发 3 200 d 地层压力分布图
注: 1 psi = 6.895 kPa。

在两端取绝流边界条件;若裂缝延伸至油藏边界,其两端的边界条件则由油藏的外边界条件确定^[9]。

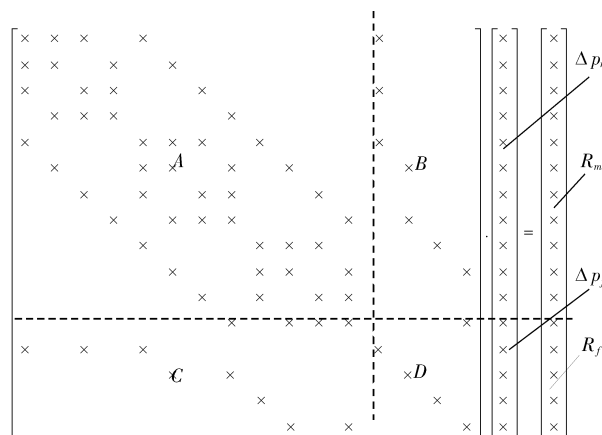


图 3 水平裂缝数值模型矩阵结构示意图

二、实例分析

根据大庆杏树岗油田萨葡油层组内低渗透非主力油层和流体的基本物性参数,建立了一注一采和两注一采两个机理模型,分别验证本文模型的可靠性和分析不同水平裂缝对油井产能和含水率的影响。

1. 模型验证

假设油层孔隙度为 0.25,基质和裂缝的渗透率分别为 10 mD 和 10 000 mD,油层厚度 10 m,压开的水平裂缝的长轴为 180 m,短轴为 90 m,无量纲裂缝导流能力为 0.3,注水井和采油井井底压力分别为 10.2 MPa 和 3.4 MPa,定压力生产 3 200 d,将本文模型的计算结果与近井网格加密模型(参考模型)、多段井近似模型和等效渗透率模型进行对比,验证本文模型的可靠性。

图 4 是本文模型和参考模型的压力场模拟结果,从中可以看到本文模型与参考模型的结果比较接近,另外两个模型均与纵向加密模型的模拟结果相差较大,主要表现为裂缝附近区域压力下降过快。

2. 不同裂缝穿透比和无量纲导流能力的影响

假设基质渗透率为 20 mD, 油层厚度 10 m, 压开的水平裂缝穿透比分别为 18%、27%、36%, 无量纲裂缝导流能力分别为 0.001 5、0.03、0.3。由于许多老油田进入特高含水阶段后普遍采取提液稳产工作制度, 注采压差很大, 因此将注水井注入压力增大至 17 MPa, 定压力生产 3 200 d, 模拟两注一采井网内油井压开水平裂缝后的产油量和含水率变化规律。其中, 水平裂缝穿透比是水平裂缝长短轴平均值与注采井距的比值。无量纲导流能力是水平裂缝渗透率和支撑宽度的乘积与基质渗透率和基质厚度

乘积的比值。

从图 5、图 6 中可以看到, 生产过程中日产油量先增大后减小, 含水率逐渐增大并趋于平缓。这是因为在 13.6 MPa 的注采压差下生产一段时间后地层压力逐渐恢复甚至部分区域大于原始地层压力。随着裂缝穿透比的增大, 产油量增大, 含水率也更高, 说明增大裂缝穿透比增产效果明显, 同时也导致更早见水。随着裂缝无量纲导流能力的不断增大, 产油量先大幅增大而后基本不变, 含水率也表现出相同的规律, 说明提高无量纲导流能力虽有助于增产但增大到一定程度后产量和含水率都基本不变。

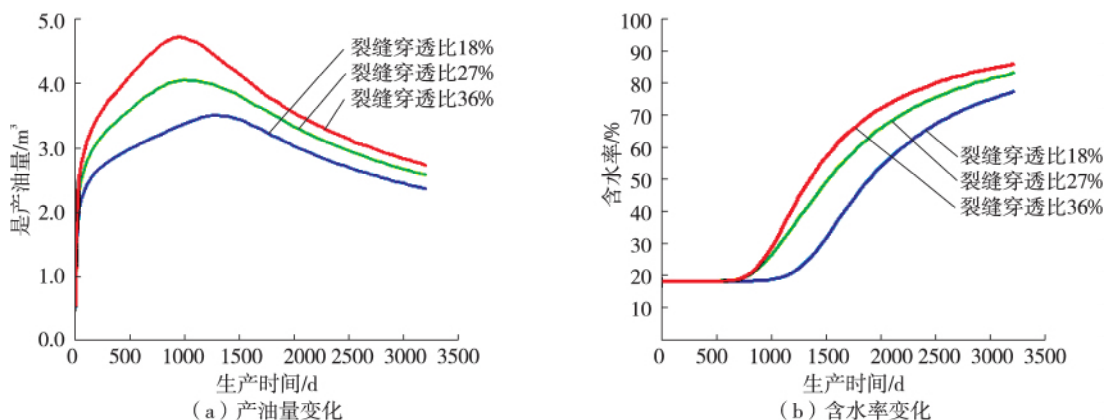


图 5 不同裂缝穿透比下产油量和含水率变化曲线

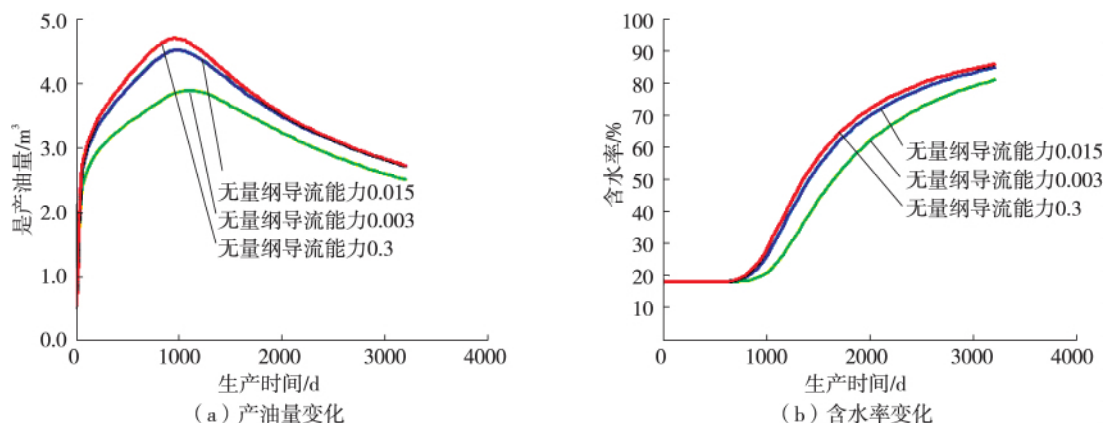


图 6 不同裂缝无量纲导流能力下产油量和含水率变化曲线

三、现场应用

根据模型验证及影响因素分析, 对水平压裂参数进行优化设计, 确定水平压裂裂缝穿透比为 27%, 无量纲导流能力为 0.015, 据此在杏六中区针对物性、含油性差的表外储层进行水平压裂开发试验, 于 2012 年底陆续投产开发井 23 口, 其中采油井 14 口, 均采用压开水平裂缝的方式开采, 注水井 9 口, 以 150 m 井距的五点注采井网开发萨尔图和葡萄花油组的表外储层。

图 7 和图 8 是水平压裂开发试验区平均单井日产油量、含水率与三次加密试验方案的对比曲线, 投产初期仅有 4 口油井, 生产效果较差, 为进一步控制表外储层潜力富集区域, 截至 2013 年 8 月又有 10 口油井陆续投产, 此时平均单井日产油量达到 1.5 t, 从 2013 年 10 月开始部署注水井, 约 3 月后开始见效, 产量稳步抬升。与同期设计的三次加密试验方案(以三类油层中薄差油层为调整对象的杏六中区井网重组)进行对比, 表外储层水平压裂开发试验区平均单井日产油量是三次加密井的 1.9 倍, 平

均含水率较三次加密井低 7.2%。

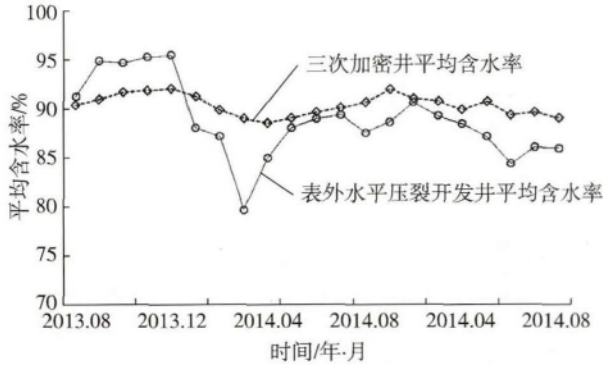


图 7 三次加密井与水平压裂开发井平均含水率对比图

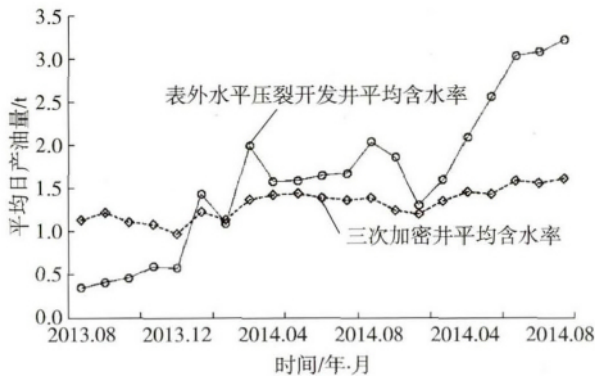


图 8 三次加密井与水平压裂开发井平均日产量对比图

四、结论

通过耦合基质和裂缝的流体流动方程,根据基质结构化网格和裂缝非结构化虚拟网格建立了离散后的数值模拟模型,提出了一种能够高效处理水平裂缝的油藏数值模拟方法,实例计算表明本文模型能够准确模拟含水平裂缝油藏内的流体流动,并利用该模型研究了大注采压差下不同裂缝穿透比和无量纲导流能力对生产动态的影响,利用设计的水平压裂缝参数在杏×中区表外储层开展矿场试验,与

同期三次加密井相比得到了更好的开发效果。

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OFFSHORE APPLICATION OF DRILLING TECHNOLOGY IN ONE CONDUCTOR WITH TWO BORES USING OCCUPIED BHA

CHEN Guohong (CNOOC Energy Technology Drilling & Production Company , Tanggu , Tianjin 300450 , China) , *DPT* 39(2) , 2016: 43 – 46

Abstract: In offshore cluster drilling and production , the production wells depend on slots in a platform. Drilling technology in one conductor with two bores not only helped to drill more wells , but improved the slot efficiency. Conventional drilling technology in one conductor with two bores couldn't drill ahead in close circuit , and couldn't build up , therefore , it was limited in practical drilling. Occupied BHA had more widely use in offshore drilling and had some advantages. It allowed to drill deep in surface section with closed circuit , vertically drill and drill in shallow gas formation. The technology has been used in Bohai 25 – 1 block and Penglai 19 – 3 , and good results have been achieved accordingly.

Key words: occupied BHA , one conductor with two bores , drilling , offshore oil/gas field

RESEARCH ON TUBING CORROSION MECHANISM AND TUBING MATERIAL SELECTION UNDER HTHP IN SHUNNAN BLOCK

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Abstract: Corrosive environment is very special in Shunnan block , such as HTHP , high CO₂ , low H₂S and hypersalinity , especially , when downhole temperature is above 200 degrees Celsius , the conventional stainless steel casing and downhole tools are difficult to meet the construction needs. How to choose the tubing material safely became the urgent problems in Shunnan block. In order to solve the problem , the corrosion about 13Cr – P110 super martensitic stainless steel , duplex stainless steel 2205 and 2507 super duplex stainless steel was studied under stimulating Shunnan block conditions , the research results showed that production pipe should adopt the combination of duplex stainless steel and nickel based alloy in Shunnan well block , nickel base alloy tubing were used in biphasic stainless steel cracking temperature sensitive area.

Key words: HTHP , stress corrosion , hydrogen sulfide , carbon dioxide

TRANSIENT PRESSURE BEHAVIOR OF FINITE – CONDUCTIVITY FRACTURED WELL IN BI – ZONAL COMPOSITE GAS RESERVOIRS

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Abstract: Hydraulic fracturing has become an efficient method to develop the low – permeability oil and gas reservoirs , which has been widely applied in the field. And , as an important approach , well testing analysis could evaluate efficient post – fracturing results and recognize the reservoir characteristics. A semi – analytical model for a finite conductivity fractured well in bi – zonal composite gas reservoir was established , which considered the fractures was fractured partially and fully. The solutions for constant production rate was obtained by the point source function and the Laplace transform techniques. Using the Stehfest numerical inversion algorithm method , the transient pressure type curves were analyzed. The models and type curves presented in this paper have both theoretically and practically valuable in well test interpretation for the related gas reservoirs.

Key words: finite conductivity fracture , bi – zonal composite gas reservoir , point source function , well test analysis

A METHOD OF NUMERICAL SIMULATION FOR RESERVOIRS WITH HORIZONTAL HYDRAULIC FRACTURES

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Abstract: It is possible to create horizontal fractures in the shallow reservoirs with high fractured pressure or vertical stress decreasing after EOR. So an efficient numerical simulation method for reservoirs with horizontal hydraulic fractures was brought forward to simulate accurately the effect of horizontal fractures on development of reservoirs based on the embedded fracture model for simulating vertical fractures. Reservoir matrixes were divided by regular grids individually , and irregular fractures grids were divided based on the polygonal intersections between horizontal fractures and matrixes , and then the contact relations of fractures' grids and matrixes' grids and wells were recorded by nonneighboring grids connections. Multiphase flow equations coupled reservoir matrixes and fractures were dispersed , and the numerical simulation model of 3D reservoir matrix and fracture system with seven – diagonal sparse coefficient matrix was constructed. The model was applied to simulate low – permeability reservoir with horizontal fractures developed by one injection well and one production well , and the simulation results were compared with local grid refinement model , multi – segment well model and permeability equivalent model , and it's closer to the local grid refinement model. Finally , taking the case of low – permeability reservoir developed by two injection wells and one production well under high injection – production pressure difference as example , the influence of different fracture length/well space ratios and dimensionless flow conductivities on the production dynamic was studied.

Key words: horizontal fracture , low permeability layer , embedded fracture model , reservoir numerical simulation , fracture length/well space ratio , dimensionless flow conductivity

RESEARCH AND APPLICATION OF WATER SHUTOFF FRACTURING TECHNOLOGY IN XIFENG FRACTURED RESERVOIR

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Abstract: According to the water – out situation in Xifeng Chang 8 fractured reservoir , only adopting water shutoff technique couldn't increase oil production , applying turnaround fracturing technology resulted in crack communicate not to realize the aim of “decreasing water”. Therefore , the experiments on reservoir reconstruction by combining water shutoff and intra – fracture turnaround fracturing techniques were carried out. Based on the geology and dynamic development features of the reservoirs , integrating technical advantages of water shutoff and turnaround fracturing , the joint technology of water shutoff and fracturing was put forward , and successfully applied in field , the purpose of “decreasing water and increasing oil” was achieved.

Key words: fracture , water shutoff , fracturing , decreasing water and increasing oil

PILOT TEST OF FINE STAGED FRACTURING TECHNOLOGY USED IN HORIZONTAL WELL IN SHAXIMIAO RESERVOIR OF XINCHANG GAS FIELD