石油科学通报
Petroleum Science Bulletin

裂缝性油气藏数值模拟与自动历史拟合研究进展

薛亮[1,2*]，吴雨娟[1,2]，刘倩君[1,2]，刘月田[1,2]，王军[3]，蒋龙[3]，程紫燕[3]

1 中国石油大学(北京)油气资源与探测国家重点实验室，北京 102249
2 中国石油大学(北京)石油工程学院，北京 102249
3 中国石化胜利油田勘探开发研究院，东营 257001
* 通信作者, xueliang@cup.edu.cn

收稿日期: 2019-07-20
本文由国家重大专项(2016ZX05037003 和 2017ZX05032004-002)、国家自然基金(51374222)、国家 973 项目(2015CB250905)、中石化科技部基础前瞻性研究项目(P18086-5)、中石化重点科技项目(P18049-1)、中石化科技部科技攻关研究项目(P18062-2) 和中国石油重大科研专项(2017E-0405) 联合支持

摘要 裂缝性油气藏在油气资源中的占比不断增加，由于储层裂缝系统定量描述的复杂性，裂缝性油气藏开发动态的准确模拟预测一直是研究的难点。本文系统地介绍了裂缝性油气藏的模拟模型，包括描述天然裂缝系统的等效连续介质模型和双重或多重介质模型，以及描述压裂裂缝的离散裂缝模型和嵌入式离散裂缝模型。历史拟合是利用实测数据调整模型参数达到提高模型模拟预测水平的重要技术。基于梯度类方法、进化算法、人工神经网络、集合卡尔曼滤波算法等自动历史拟合方法，在油藏开发实践中得到广泛应用。微震数据能够提供压裂裂缝分布的重要信息，在自动历史拟合的过程中，可以和生产数据共同约束模型参数的多解性。

关键词 裂缝性油藏；自动历史拟合；微震监测

Advances in numerical simulation and automatic history matching of fractured reservoirs

XUE Liang[1,2], WU Yujuan[1,2], LIU Qianjun[1,2], LIU Yuetian[1,2], WANG Jun[3], JIANG Long[3], CHENG Ziyan[3]

1 State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum-Beijing, Beijing 102249, China
2 Department of Oil-Gas Field Development Engineering, College of Petroleum Engineering, China University of Petroleum-Beijing, Beijing 102249, China
3 Exploration and Development Research Institute, Shengli Oilfield Company, Dongying 257001, China

Abstract Fractured reservoirs are becoming increasingly important in reservoir engineering. However, due to the complexities of the fracture systems, it is difficult to predict well performance in fractured reservoirs. The dominant numerical models to deal with fractured reservoirs are introduced. These include the equivalent continuum model, the dual media model, the discrete fracture model and the embedded discrete fracture model. History matching is an essential process to improve the model predictability by using production data. A variety of automatic history matching methods have been developed, such as the gradient-based method, the evolutionary algorithm, the artificial neural network method and the ensemble Kalman filter method. Microseismic data can provide useful information to constrain modeling of the hydraulic fracture distribution, and can be used jointly with production data to improve the model prediction.

引用格式：薛亮, 吴雨娟, 刘倩君, 刘月田, 王军, 蒋龙, 程紫燕. 裂缝性油气藏数值模拟与自动历史拟合研究进展. 石油科学通报, 2019, 04: 335-346
XUE Liang, WU Yujuan, LIU Qianjun, LIU Yuetian, WANG Jun, JIANG Long, CHENG Ziyan. Advances in numerical simulation and automatic history matching of fractured reservoirs. Petroleum Science Bulletin, 2019, 04: 335-346. doi: 10.3969/j.issn.2096-1693.2019.04.030

Keywords fractured reservoir; automatic history matching; microseismic monitoring

doi: 10.3969/j.issn.2096-1693.2019.04.030

0 引言

随着全球低渗透油气藏勘探和压裂改造技术的进步，裂缝性油气藏的生产开发也变得越来越普遍。裂缝作为该类油气藏储层中油气渗流的主要通道，其位置分布及属性特征对油气藏产能的影响至关重要，因此精确模拟油气藏中裂缝的形态及其渗流特征具有非常重要的意义。油藏数值模拟的方法由刻画天然裂缝的等效连续介质和双重介质(或多重基质[1])模型，过渡到刻画压裂裂缝的离散裂缝模型。历史拟合是进行准确参数反演和模拟预测的必要环节，油藏自动历史拟合技术基于随机理论方法，逐渐在实际油田开发实践中得到广泛应用。裂缝性油气藏由于裂缝大量发育，导致其历史拟合较常规油气藏更加复杂，传统的人工历史拟合方法效率低下且效果无法保证。而自动历史拟合技术不仅能够大幅提高其拟合效率，且可以减少人为主观因素的干预，精确定量的描述拟合效果。由于自动历史拟合存在多解性，自动历史拟合的初始值越符合实际，则拟合结果越精确。为了进一步提高拟合效率并真实反映油气藏储层特征，考虑使用微震监测裂缝表征技术来得到初始的裂缝分布状态及几何参数，约束自动历史拟合过程的参数求解范围，得到更加接近现场实际的油藏模型，从而为油藏生产开发提供理论指导。

1 裂缝性油气藏数值模拟方法

油气藏数值模拟是针对地下油气藏管理最为有效的技术，其有助于理解油气藏开采过程并优化生产决策。最新裂缝模拟技术研究成果使优化和提高有机页岩储层的生产成为可能[2–3]。在对裂缝性油气藏模拟时，最关键的问题是如何处理裂缝网络与基质体系的相互作用。目前提出了多种模型，以不同假设来模拟裂缝性储层中的流体流动[4–11]。这些方法包括：(1)等效连续介质模型[12]；(2)双重介质模型[13–14]，包括双孔单渗模型和双孔双渗模型；(3)多重基质模型[15–17]；(4)离散裂缝模型[18–19]。各类模型描述如下。

1.1 等效连续介质模型

等效连续模型首先由Snow(1968)[18]提出。此后Wu(2000)等提出不同假设条件表征不同类型等效连续体模型，如等温流动，流体和热传导的耦合，单相流和多相流[12]。在等效连续介质模型中，裂缝多孔介质被认为是连续介质。裂缝组的诸多性质(例如方向，位置，渗透率，孔隙度等)被平均化处理到整个多孔介质中。该方法专注于研究多孔介质宏观流动特性，而不考虑单个裂缝中具体流动条件。这种方法在油气藏模拟中尚未得到广泛应用，因为它不易获得平均渗透张量，而且太过概念化。Moridis等人(2010)建立了考虑多组分气体吸附的有效连续油气藏模拟模型[20]。Cipolla等(2009)以及Cheng(2012)认为在等效连续模型中，页岩气储层是离散的，裂缝的特征被表述为网格单元中的单平面或平面组成的网络系统[21–22]。

1.2 双重介质模型

双重介质概念(如图1)最早是由Barenblatt和Zheltov(1960)提出[23]。此后双重介质概念通过Warren和Root(1963)被引入到石油工程研究[13]。大量文献[24–30]将双重介质模型广泛应用于模拟裂缝性多孔介质的流体流动研究中。双重介质模型考虑两种相互作用的不同介质：一类是孔隙度高、渗透率低的基质块体；另一类是孔隙度低、传导率高的裂缝网络。根据基质中是否有流体流动，双孔隙度模型可以进一步划分为双孔单渗模型(Dual Porosity Single Permeability, DP)和双孔隙双渗模型(Dual Porosity Dual Permeability, DPDP)。

双孔单渗模型的流体流动仅发生在裂缝系统中，而基质被视为裂缝系统在空间分布中的汇或源项[31]。在油气藏中，基质体系作为油气储存空间，裂缝系统作为高渗透率的流动通道。Watson等人(1990)使用DPM对泥盆纪油气藏生产数据进行分析，并提出了用于历史拟合和产量预测的油藏生产分析模型[32]。Bustin等人(2008)构建了用于模拟油气藏的二维双重介质模型，其使用实验和现场数据作为模型输入参数，流体流动遵循达西定律[6]，耦合控制方程采用在时间和空间上隐式离散化的有限差分法。Du(2010)应用双重孔隙介质模拟了水力压裂改造后的油气藏[33]。应用微震进行水力压裂处理数据和生产历史拟合研究等。Ozkan等人(2010)开发了双重基制—双重孔隙度模型来模拟油气藏裂缝水平井的线性流动[8]。

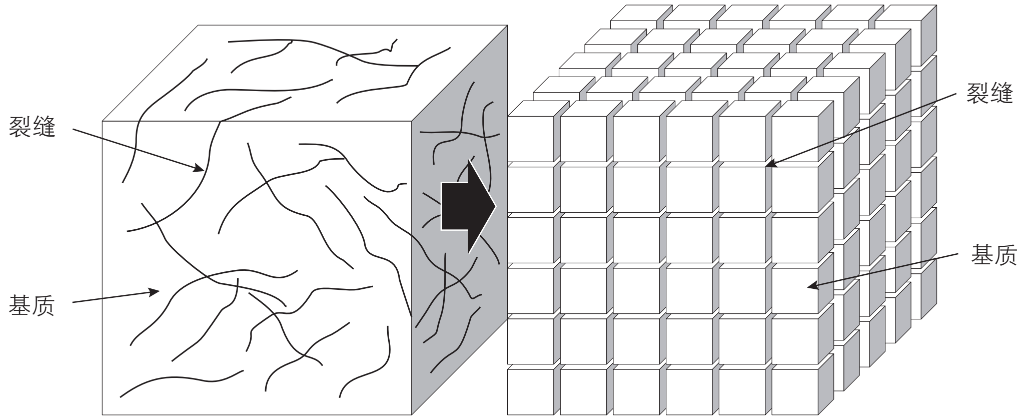

图 1　双重介质模型示意图

Fig. 1　Schematic diagram of DPDP model[13]

双孔双渗模型与双孔单渗模型不同之处在于，该模型在裂缝渗流基础上也考虑了流体在基质中的流动[34−35]。基质属性参数控制从基质到裂缝的流体流动。Connell和Lu(2007)提出了考虑裂缝中达西流动和基质中页岩气扩散的双孔模型[36−37]。Moridis(2010)构建了双重渗透率模型，并将其与双孔单渗模型和等效连续模型进行了比较[20]。结果表明，双渗透率模型提供了最佳的生产性能，在生产后期，偏差会变得更加明显。Ren等人(2010)提出了基于双孔隙双渗透率模型的油气藏模拟模型[38]，该模型考虑了吸附—解吸附、扩散、黏性流动和变形等多种流动机制。

1.3　离散裂缝模型

在离散裂缝模型中(如图2)，储层内每根裂缝被离散地进行模拟。裂缝的建模需要使用基于Delaunay三角剖分的基质裂缝系统的非结构化网格,每根裂缝被描述为几何形态明确的实体。Baca等人(1984)提出一种使用DFM(discrete fracture model)的裂缝性油藏溶质、热流二维模型[40]。Juanes等人(2002)使用有限元DFM研究了二维和三维单相流在裂缝储层中的流动[41]。Karimi-Fard等人(2003)提出一种使用有限体积法结合非结构化网格的简化离散裂缝模型，该模型可用于二维和三维多相流体流动的模拟[42]。Gong(2008)提出了一个使DFM能够适用于油藏尺度的工作流程[43]。

1.4　嵌入式离散裂缝

2001年，Lee等人[44]结合双重介质模型和离散裂缝模型的优点，提出了嵌入式离散裂缝模型(EDFM)，如图3所示。利用结构化网格嵌入裂缝的方法对垂直裂缝进行数值模拟实验，获得了很好的拟合效果。该

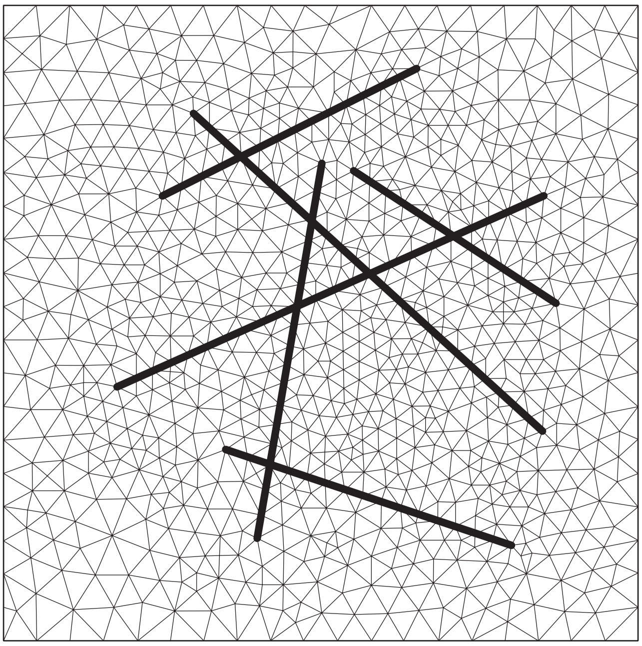

图 2　离散裂缝模型示意图

Fig. 2　The diagram of discrete fracture network model[39]

模型主要原理是通过使用正交结构化网格对油藏进行划分，将裂缝嵌入基质网格中。避免了使用非结构化网格剖分油藏模型所带来的较大计算量问题。在进行数值求解时，将裂缝视为基质网格中的井源，使用类Peaceman公式来计算两种介质间的流量交换。

Moinfar[45]在嵌入式离散裂缝(EDFM)基础上推导了全隐式组分模型，进一步改进了该模型。该模型可以同时显式表征裂缝，而且裂缝可以是任意角度的，能够在模型中很好的刻画裂缝复杂性和储层非均质性特点。在嵌入式离散裂缝模型基础上，利用单侧插值方法计算流量交换，可以提高裂缝模型的精度和计算效率[46]。冯其红和徐世乾等人基于嵌入式离散裂缝模

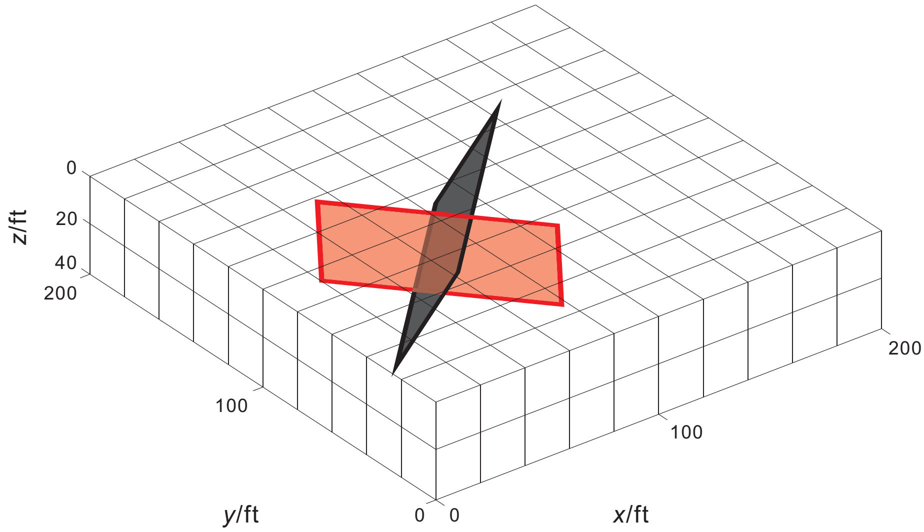

图 3 嵌入式离散裂缝模型图

Fig. 3 Embedded discrete fracture model diagram[45]

型,建立了页岩气藏视渗透率模型，对影响页岩储层视渗透率的参数进行评估，得出天然裂缝比无机质和有机质孔隙贡献更大的结论[47]。严霞和黄朝琴等人提出了离散缝—洞网络混合模型(Discrete Fracture–Vug Model, DFVM)，小裂缝和孔洞采用等效连续介质方法(ECM)模拟，长裂缝作为主要的渗流通道采用嵌入式离散裂缝网格(EDFM)模拟，并利用基于有限差分方法(Mimetic Finite Difference method, MFD)的数值模拟算法来求解该混合模型，该混合模型的有效性与精确性通过几个数值模拟案例得到了验证[48]。戴城和薛亮等人在嵌入式离散裂缝模型基础上，分析了游离气和吸附气在页岩气生产过程中的移动和贡献,研究了页岩基质、次生天然裂缝网络、原生水力裂缝等关键储层性质对采收率的影响[49]。吴明录等人基于嵌入式离散裂缝模型对页岩气藏参数敏感性进行分析[50]。

2 裂缝性油气藏自动历史拟合

油气藏自动历史拟合也被称作参数反演，其本质上是求解油气藏目标函数最小值的方法。常见的目标函数较多，在确定其具体形式情况下，不同参数反演方法的差异在于选取何种最优化算法。求解函数最小值的方法可以分为两种：基于梯度的方法与非梯度方法。

2.1 梯度类方法

梯度类方法简单且收敛效果好、应用广泛，常见的梯度求解方法有数值扰动法、直接求解法、伴随方程法等。

数值扰动法基于有限差分原理求解梯度。确定要研究的参数后，通过固定其余参数值，对所研究参数加扰动并观测它对观测数据的扰动，即可根据差分方程求解观测数据对该参数的导数。在这个过程中需要进行正问题计算，因此使用该方法处理含有大量模型参数的问题时非常困难。

直接求解方法要构造模型状态变量对模型参数导数满足的方程。该方程与原有油藏模拟方程形式一致，求解时需要对每一个参数的导数方程求解。Anterion 等[51]首次将直接求解法用于自动历史拟合敏感性参数分析中。Bissell 等[52]应用直接求解法计算历史拟合中的敏感系数。但是该方法在处理大规模的油藏问题时，由于模型参数数量过大而难实现。

利用伴随方程法求解某一观测对所有模型参数的导数时，只需构造并求解一个相应的伴随方程，效率较高。该方法的难点在于伴随方程的建立与维护。Jacquard 等[53]于 1965 年首次运用近似伴随法对两维单相瞬时流模型进行了历史拟合。Chen 等[54]和 Chavent 等[55]采用伴随法对最优控制问题进行求解。

2.2 进化算法

与传统的优化算法相比，进化算法更稳定且适用性更广。利用单个油藏模型的突变和重组产生新的油藏模型是进化算法通常采用的方法，根据数据不吻合度的适应度函数决定新模型是否可以作为合格的油藏储备模型。遗传算法和进化策略算法是其最常见的两种进化算法形式。Romero 和 Carter 应用遗传算法进行与油藏测量值相匹配的储层描述，该方法已在真实、

复杂的油藏模型上进行了测试，并通过比较证明遗传算法与手工实现的结果相当，比模拟退火算法效果更好。考虑到该方法容易并行化以及强鲁棒性，它是一种油藏自动描述算法的理想方法[56]。进化策略为自适应的优化方法，可以在目标函数最小值邻域收敛。Schulze-Riegert将优化环境支持的历史拟合方法应用于不同的复杂油藏模型。在优化循环的过程中，模拟运行是由一个目标函数(包含了生产数据随时间变化的关系)指导的。贝叶斯方法被作为全局的搜索方法用于识别最优参数集合，提高了进化算法计算的收敛性。在多目标并行优化环境下，应用进化策略算法对合成模型进行历史拟合，经过10代进化，目标函数的值降低了70%[57]。Perez等[58]根据进化策略的算法特点，将其应用于墨西哥某裂缝性油藏的历史拟合中实现最优化模拟时间，该历史拟合方法采用了嵌入式离散缝网模型并考虑了井的水窜问题，结果表明，进化策略算法不仅比传统算法节省了近75%的历史拟合时间，而且经进化策略优化后的油藏模型也比传统算法优化后的模型更可靠。然而，进化算法的问题是收敛速度慢，Schulze-Riegert等采用降维方式来提高进化算法的收敛速度[56]。

2.3 人工神经网络

人工神经网络自身可适应环境、总结规律、完成某种运算，通过学习从有限的油藏资料中找到最优解，具有强非线性动态处理能力；其并行计算能力强，容错能力和稳定性较好。因此该方法应用于自动历史拟合得到的反演结果稳定，趋于合理，可提高自动历史拟合的可靠性。人工神经网络在油藏自动历史拟合中的应用主要有两种，一是直接最小化目标函数，二是作为油藏模拟器的替代模型[59]。ANN方法还通过不断与其他方法结合，形成了较好的混合优化算法[60]。

2.4 集合卡尔曼滤波算法

传统历史拟合方法针对当前时刻的所有历史数据，当后产生的新数据可用时，最小化目标函数则被改变。这类特征使得传统拟合方法效率不佳，耗时耗力。基于集合卡尔曼滤波的油气藏自动历史拟合方法是建立在贝叶斯理论之上的一类顺序同化方法，新产生的数据可以通过EnKF(Ensemble Kalman Filter)及时被同化进参数模型，更新后的参数场可以保留对历史数据的预测能力，而下次更新仅需从当前时刻向前推进，大大提高了历史拟合的效率[61]。特别是裂缝性油气藏模型中裂缝是影响产量的重要因素从而需要进行历史拟合的参数众多，引入EnKF方法来更新裂缝性油气藏中的模型参数能够大大提高历史拟合效率，以达到对裂缝性油气藏渗流系统的准确模拟，对指导裂缝性油气藏生产开发有很重要的作用。

集合卡尔曼滤波理论首次被Evensen于1994年被引入[62]，其通过一组随机实现来近似估计状态系统，利用这些集合实现在相空间的运动来确定模型的不确定性。EnKF是一类最小均方随机状态估计工具，特点是测量值可以被顺序地同化以更新状态估计。EnKF在石油工程的首次应用[63]是近井储层监测数据的辅助历史拟合，Nævdal等人成功应用EnKF不断更新两注一采油藏机理模型的模型参数以及北海油田简化模型的模型参数。自从它首次应用于油气藏工程以来，EnKF已被广泛用于油气藏自动历史拟合工作[64–65]。并已被Lorentzen等在PUNQ-S3模型上利用EnKF来估计模型孔隙度场和渗透率场的相关初始实现的鲁棒性[66]，以及如何利用先验知识来获得更具代表性的初始实现。

针对EnKF高斯假设的前提，许多文献[67–70]研究了EnKF的非高斯随机场应用推广问题。对多岩石相分布的强非高斯场，结合截断高斯法的EnKF是一类典型处理方式，该方法被Agbalaka和Oliver与Zhao等人用于研究三维多岩石相分布的反演问题，并取得了较好的同化效果[71–72]。Moreno和Aanonsen提出利用Level set函数对相边界进行隐式表达并将其演化速度在高斯场中更新的方法，以此实现岩石相分布估计[73]。此外还可通过离散余弦变换来参数化模型、状态变量，经更新后的余弦函数系数被用来重构模型参数与状态变量[74–75]以及高斯混合模型等处理方法[76]。

针对EnKF处理强非线性问题时参数更新过程的参数非物理性问题，多种迭代EnKF方法实现对模型参数与状态变量进行了物理性约束：Wen和Chen及Gu和Oliver分别提出了简单迭代和基于极大似然估计迭代的EnKF方法[77–78]。而对于小样本量造成的协方差矩阵奇异值现象，可通过引入不同的局部化函数方法进行约束。

目前，有许多学者将自动历史拟合方法应用于裂缝系统的模拟中。Lu和Zhang对天然裂缝参数化处理，并且采用迭代ES作为逆建模方法[79]。Liu 和Dai将集合卡尔曼滤波器(EnKF)与DFM(离散裂缝模型)相结合，通过拟合历史生产数据估计裂缝分布[80]。其中，每个裂缝的空间分布由端点、长度和方向的坐标表征。在历史拟合过程中，这些几何属性被视为可调整的模型参数。Dachanuwattana和Xia等人结合自动历史拟合与嵌入式离散裂缝方法，对加拿大Duvernay页岩凝析

油藏进行了历史拟合[81]。

3　微震监测裂缝表征技术

3.1　微震监测机理

水力压裂是油气藏开采的至关重要的技术，在水力压裂作业过程中，需要监测裂缝扩展路径和几何形态，以准确估计油藏体积压裂改造区域(Stimulated Reservoir Volume, SRV)、评价压裂效果并进行产能预测[82]，因此理解复杂水力压裂裂缝对于非常规资源经济有效开发至关重要[83]。其中，微地震技术可以对水力压裂产生的复杂裂缝网络进行成像和监测，被广泛应用于非常规储层压裂缝网几何形态和油藏应力分布等描述[84]。微地震监测技术发源于地震学和声发射学，它是一种以生产活动中所产生的微小地震事件观测和分析为基础，对该活动的影响、效果与地下状态进行监测的地球物理技术[85]。Warpinski等认为微震事件的发生是由于流体漏失进入天然裂缝和其他渗透薄弱层面，导致应力和孔隙压力变化，并引起小规模地层移动[86]。水力压裂过程中，岩石破裂并以微地震波的形式释放储存在岩石中的能量，引起微小地震以及声发射现象的产生，这种释放出的地震能量能够被井中或者地面上设置的高灵敏度的检波器探测到(如图 4 所示)，通过数据处理可以确定震源在时间和空间上的分布[86]。如果确定了压裂裂缝产生的微地震震源的空间位置，则可以得到裂缝所延伸的方向以及裂缝的长、宽、高等相关的参数进而估算储层压裂改造体积(Stimulated Reservoir Volume, SRV)[87]。

3.2　基于微震数据的裂缝建模方法

微地震技术的应用不仅体现在成像和监测上，随着微地震信息解释的深入，将微地震获得的信息与地质、地球物理、测井数据等信息集成，应用到数值模拟中，可以更加准确地模拟复杂裂缝网络气藏，优化生产预测[89]。微震解释裂缝形态需要充分理解压裂过程中岩石力学原理[82]。很多学者提出了基于微震事件的不同裂缝表征方法。Maxwell根据每个压裂段微震点分布趋势得到的直线表示裂缝[90]。Fisher根据微震事件的时间以及线性回归算法(如图 5 所示)，确定了与累积产量相关的缝网尺度[91]。2010 年，Mayerhofer将包含每个对生产有贡献的微震点的网格用于计算油藏压裂改造体积[92]。然而，只依靠微震数据会产生一定的错误，因为微震数据只能表征裂缝的方位不能表征裂缝的支撑开度[83]，水力压裂微地震事件受到地应力、天然裂缝、地质构造、储层特征等多种因素的影响[93–94]，并且还伴随着设备噪声等具有干扰性的信息[95]。因此微震数据需要和裂缝模型结合才能更加精确的描述对生产贡献的裂缝几何尺度。为了描述压裂缝网，Xu等提出由两个垂直集合的垂直裂缝组成的丝网状模型(wire meshed model)来模拟复杂缝网[96]。为了更精确地描述缝网，一种用微震信息来矫正裂缝的离散缝网模型(Discrete Fracture Network, DFN)[41][97]得到了发展。离散缝网模型可由大尺度的微震数据或小尺度的岩心分析数据等获得[98]。为了构建离散缝网模型，Kanamori将裂缝面放置在微地震事件的位置，裂

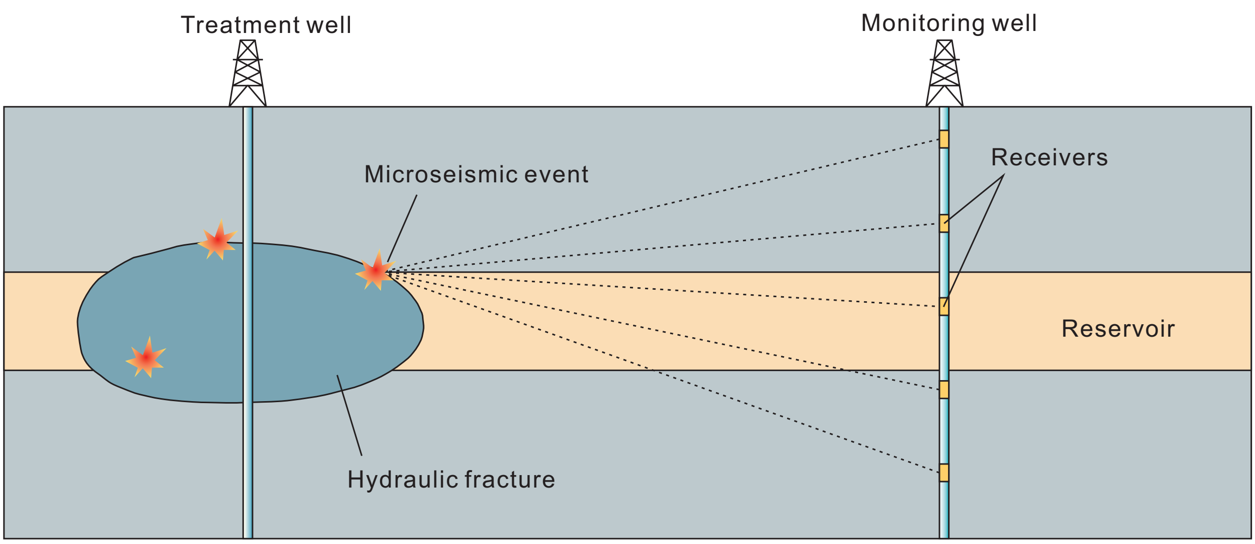

图 4　微地震压裂井下监测示意图[88]

Fig. 4　The diagram of microseismic fracturing downhole monitoring

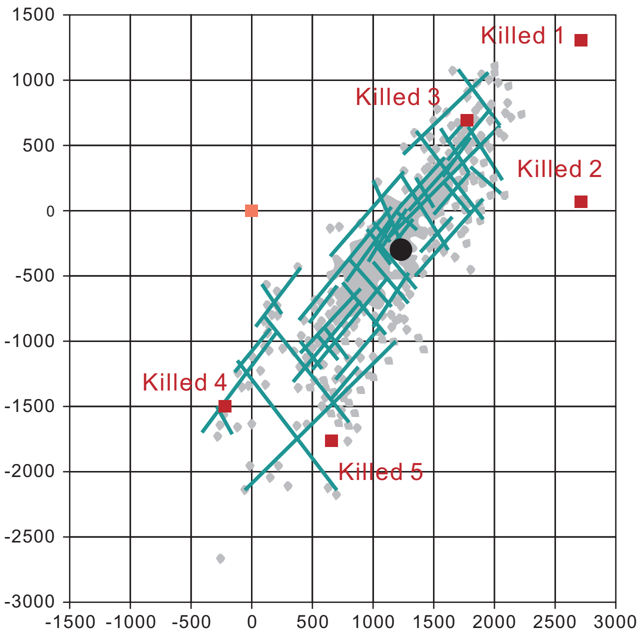

图 5　一口直井的裂缝描绘示意图(灰色点为微震事件，绿色的线表示裂缝，黑色的点表示井，横纵轴代表区域相对坐标)[91]

Fig. 5　An example of fractures mapping in a vertical well (grey points are microseismic events, green lines indicate fractures, black dot indicates well)

缝的面积和开度根据事件的震级估计[99]，裂缝的方向由震源属性特征确定[100]。Cipolla利用非常规裂缝模型(Unconventional Fracture Model, UFM)和考虑微震数据的丝网状模型(wire meshed model)来表示复杂水力裂缝[88]。利用离散缝网模型(DFN)来模拟由测井、微震等信息得到的复杂水力裂缝[101]从而实现非常规裂缝模型(UFM)应用。Hu等利用蚂蚁追踪算法通过微震事件提取裂缝尺寸、形态以及断层几何来获取嵌入式离散缝网[102]。但由于离散缝网导致计算效率较低，一种新的可高效计算离散缝网的嵌入式离散裂缝网格(Embedded Discrete Fracture Model, EDFM)建模方法被广泛应用[44–45]。Shakiba等将嵌入式离散裂缝模型与微震数据相结合进行油藏生产模拟分析，结果表明EDFM(如图6所示)与非结构网格剖分方法相比在保证对裂缝刻画精确度可接受的前提下计算效率更高，该方法为研究不同的嵌入式离散缝网实现提供了一种鲁棒、高效的方法[103]。除此之外，模拟结果表明油藏生产动态对于裂缝的几何形态、连通性及导流能力等参数极其敏感，然而，由于微震数据及裂缝描述方法的不确定性，初始裂缝模型依旧具有一定程度的不确定性，因此，通过历史拟合进行参数调整是十分必要的。

3.3　微震数据结合生产数据的裂缝模型反演

随着数据采集设备和数据处理算法的不断改进，基于微震的裂缝解释技术在一定程度上可得到较为详细的复杂水力裂缝的几何形态。然而，由微震导出的裂缝模型仍然存在一定程度的不确定性。为了进一步修正裂缝模型参数，需要结合生产数据进行历史拟合。将微震数据与生产数据相结合校正裂缝属性被认为是一种有效的裂缝建模方法[104]。Clarkson通过实例分析表明，裂缝监测数据(如微震和压裂后生产测井数据)对致密储层压裂水平井的模型建立和验证起到重要作用[105]。Yin等(2011年)[106]和Xie等[107]基于历史拟合理论，采用改进遗传算法(Genetic Algorithm, GA)对裂缝和储层性质进行估计，将微震数据结合到历史拟合中，调整油藏体积压裂改造区(SRV)，并对井态进行预测。Wu等通过综合岩心、微震活动、生产和增产措施的诊断数据，建立了校正后的裂缝模型，降低了裂缝复杂程度对裂缝几何形状描述的不确定性[108]。Zhou等利用微震数据矫正裂缝几何形态，生产动态分析(rate transient analysis, RTA)用于解释生产数据并估算缝网参数，而生产数据用于验证和调整裂缝属性参数[105]。Fan等于2017年在现有裂缝密度及微震信息和现场生产数据的基础上，建立压裂的非均质页岩气生产综合模型，并通过历史拟合验证模型的有效性，从而进行生产动态预测[109]。Patterson等人于2018年综

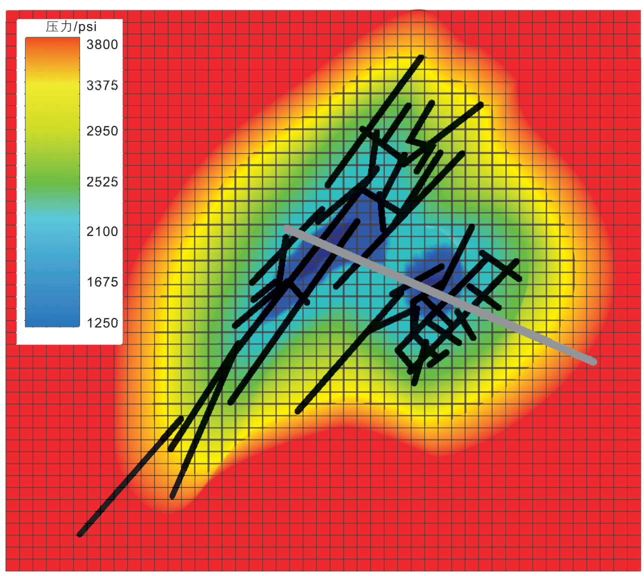

图 6　由EDFM(嵌入式离散裂缝网格模型)建立的复杂缝网模型生产30年的压力剖面(等值线代表压力)[103]

Fig. 6　Pressure profile after 30 years production modeled through complex fracture network with EDFM

合微震活动、增产措施和生产数据来校准模型，提高了裂缝几何形状描述的可靠性[110]。

因此，微震监测数据对于裂缝形态和几何参数(长、宽、高、方位角、倾角)表征及裂缝建模具有重要意义。进一步将微震数据与生产、压力等数据结合对于裂缝模型校正和验证以及储层体积压裂改造区(SRV)的估计、生产预测至关重要，从而更完善地为油田管理提供合理的依据。

4 结论

通过本论文的文献综述分析，主要可以得出以下几个结论：

(1) 模拟裂缝性油气藏的模型大致可分为 4 种，其中应用较为广泛的有双重介质模型和离散裂缝模型。双重介质模型仅适用于相互连通且密集分布的裂缝，该方法在模拟大尺度导流裂缝时难度较大。离散裂缝模型采用非结构化网格使得裂缝与基质网格相匹配，这种处理方式能够保证裂缝几何形状和性质保持一致，但是网格剖分过程复杂，计算困难。嵌入式离散裂缝方法借鉴了双重介质概念，同时考虑了储层中单独存在的每条裂缝的影响，使用正交结构网格对基质进行划分，裂缝嵌入其中，实现了对裂缝发育的页岩气藏网格高效划分，从而提高计算效率。

(2) 集合卡尔曼滤波算法可以对油藏模型参数连续更新，可以定量分析评估油气藏模拟预测的不确定性。与传统历史拟合方法相比，EnKF算法不需要进行敏感系数矩阵计算，但是其算法自身仍然有局限性。在实际应用中，EnKF在解决复杂的非线性问题和同化高频率实测数据中等还有一些问题需要解决。

(3) 根据微震事件表征油气藏裂缝分布形态及几何参数，通过微地震定位方法可以确定有效支撑裂缝位置、起裂时间，在一定程度上可初步反映裂缝性油气藏的裂缝分布情况。

(4) 综合使用微震监测技术以及自动历史拟合方法，结合对裂缝描述精确并且计算效率高的嵌入式离散裂缝模型来模拟刻画裂缝性油气藏，将会大幅提高该类油气藏的数值模拟效率和模拟的效果。

参考文献

[1] DEHGHANPOUR H, SHIRDEL M. A triple porosity model for shale gas reservoirs[C]// Canadian Unconventional Resources Conference, Calgary, Alberta, Canada, 15−17 November, 2011. SPE 149501.

[2] LEE W J, SIDLE R. Gas-reserves estimation in resource plays[J]. SPE Economics & Management, 2010, 2(02): 86−91.

[3] KALANTARI D A, ESMAILI S, MOHAGHEGH S D. Fast track analysis of shale numerical models[C]// SPE Canadian Unconventional Resources Conference, Calgary, Alberta, Canada: Society of Petroleum Engineers, 2012.

[4] LUFFEL D L, HOPKINS C W, S C. Matrix Permeability Measurement of Gas Productive Shales [C]//SPE annual technical conference and exhibition, Houston, Texas: Society of Petroleum Engineers, 1993.

[5] MAYERHOFER M J, LOLON E P, YOUNGBLOOD J E, et al. Integration of microseismic-fracture-mapping results with numerical fracture network production modeling in the Barnett Shale[C]//SPE annual technical conference and exhibition, San Antonio, Texas, USA: Society of Petroleum Engineers, 2006.

[6] BUSTIN A M M, BUSTIN R M, CUI X. Importance of fabric on the production of gas shales[C]//SPE unconventional reservoirs conference, Keystone, Colorado, USA: Society of Petroleum Engineers, 2008.

[7] RUBIN B. Accurate simulation of non Darcy flow in stimulated fractured shale reservoirs[C]//SPE Western regional meeting, Anaheim, California, USA: Society of Petroleum Engineers, 2010.

[8] OZKAN E, RAGHAVAN R S, APAYDIN O G. Modeling of fluid transfer from shale matrix to fracture network[C]//SPE Annual Technical Conference and Exhibition, Florence, Italy: Society of Petroleum Engineers, 2010.

[9] FAZELIPOUR W. Innovative reservoir modeling and simulation of unconventional shale gas reservoirs powered by microseismic Data[C]//SPE Middle East Unconventional Gas Conference and Exhibition, Muscat, Oman: Society of Petroleum Engineers, 2011.

[10] SHABRO V, TORRES-VERDIN C, JAVADPOUR F. Numerical simulation of shale-gas production: From pore-scale modeling of slip-flow, Knudsen diffusion, and Langmuir desorption to reservoir modeling of compressible fluid[C]//North American Unconventional Gas Conference and Exhibition, The Woodlands, Texas, USA: Society of Petroleum Engineers, 2011.

[11] ALNOAIMI K R, KOVSCEK A R. Experimental and numerical analysis of gas transport in shale including the role of sorption[C]//SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA: Society of Petroleum Engineers, 2013.

[12] YU S W. On the effective continuum method for modeling multiphase flow, multicomponent transport and heat transfer in fractured rock[J]. Office of Scientific & Technical Information Technical Reports, 2000，122：299−312.

[13] WARREN J E, ROOT P J. The behavior of naturally fractured reservoirs[J]. Society of Petroleum Engineers Journal, 1963, 3(03): 245−255.

[14] KAZEMI H. Pressure transient analysis of naturally fractured reservoirs with uniform fracture distribution[J]. SPE Journal, 1969, 9(04): 451−462.

[15] CIVAN F, RAI C S, Sondergeld C H. Shale-gas permeability and diffusivity inferred by improved formulation of relevant retention and transport mechanisms[J]. Transport In Porous Media, 2011, 86(3): 925−944.

[16] DEHGHANPOUR H, SHIRDEL M. A triple porosity model for shale gas reservoirs[C]//Canadian Unconventional Resources Conference, Calgary, Alberta, Canada: Society of Petroleum Engineers, 2011.

[17] YAN B, WANG Y, KILLOUGH J E. Beyond dual-porosity modeling for the simulation of complex flow mechanisms in shale reservoirs [J]. Computational Geosciences, 2016, 20(1): 69−91.

[18] SNOW D T. A parallel plate model of fractured permeable media[D]. San Francisco: University of California, Berkeley, 1965.

[19] XIONG X, DEVEGOWDA D, VILLAZON M, et al. A fully-coupled free and adsorptive phase transport model for shale gas reservoirs including non-Darcy flow effects[C]//SPE annual technical conference and exhibition, San Antonio, Texas, USA: Society of Petroleum Engineers, 2012.

[20] MORIDIS G J, BLASINGAME T A, FREEMAN C M. Analysis of mechanisms of flow in fractured tight-gas and shale-gas reservoirs [C]//SPE Latin American and Caribbean Petroleum Engineering Conference, Lima, Peru: Society of Petroleum Engineers, 2010.

[21] CIVAN F. Effective correlation of apparent gas permeability in tight porous media[J]. Transport in porous media, 2010, 82(2): 375−384.

[22] CHENG Y. Impact of water dynamics in fractures on the performance of hydraulically fractured wells in gas-shale reservoirs[J]. Journal of Canadian Petroleum Technology, 2012, 51(02): 143−151.

[23] BARENBLATT G I, ZHELTOV I P, KOCHINA I N. Basic concepts in the theory of seepage of homogeneous liquids in fissured rocks strata[J]. Journal of Applied Mathematics and Mechanics, 1960, 24(5): 1286−1303.

[24] DE SWAAN O A. Analytic solutions for determining naturally fractured reservoir properties by well testing[J]. Society of Petroleum Engineers Journal, 1976, 16(03): 117−122.

[25] KUCUK F, SAWYER W K. Transient flow in naturally fractured reservoirs and its application to Devonian gas shales[C]//SPE Annual Technical Conference and Exhibition, Dallas, Texas: Society of Petroleum Engineers, 1980.

[26] ZIMMERMAN R W, BODVARSSON G S. Integral method solution for diffusion into a spherical block[J]. Journal of Hydrology, 1989, 111(1−4): 213−224.

[27] ZIMMERMAN R W, CHEN G, HADGU T, et al. A numerical dual-porosity model with semianalytical treatment of fracture/matrix flow[J]. Water Resources Research, 1993, 29(7): 2127−2137.

[28] LAW D H S, VAN DER MEER L G H, GUNTER W D. Numerical simulator comparison study for enhanced coalbed methane recovery processes.Part I: Pure carbon dioxide injection[C]//Paper SPE 75669 presented at the SPE Gas Technology Symposium, Calgary, Alberta, Canada, 2002.

[29] SHI J Q, DURUCAN S. A bidisperse pore diffusion model for methane displacement desorption in coal by CO_2 injection[J]. Fuel, 2003, 82(10): 1219−1229.

[30] OZKAN E, RAGHAVAN R S, APAYDIN O G. Modeling of fluid transfer from shale matrix to fracture network[C]//SPE Annual Technical Conference and Exhibition, Florence, Italy: Society of Petroleum Engineers, 2010.

[31] WU Y S, MORIDIS G J, BAI B, et al. A multi-continuum model for gas production in tight fractured reservoirs[C]//SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas: Society of Petroleum Engineers, 2009.

[32] WATSON A T, GATENS J M, LEE W J, et al. An analytical model for history matching naturally fractured reservoir production data[C]//SPE Production Operations Symposium, Oklahoma City, Oklahoma: Society of Petroleum Engineers, 1989.

[33] DU C M, ZHAN L, LI J, et al. Generalization of dual-porosity-system representation and reservoir simulation of hydraulic fracturing-stimulated shale gas reservoirs[C]//SPE Annual Technical Conference and Exhibition, Jakarta, Indonesia: Society of Petroleum Engineers, 2011.

[34] PEREIRA C A, KAZEMI H, OZKAN E. Combined effect of non-Darcy flow and formation damage on gas well performance of dual-porosity and dual-permeability reservoirs[J]. SPE Reservoir Evaluation & Engineering, 2006, 9(05): 543−552.

[35] YAN B, WANG Y, KILLOUGH J E. Beyond dual-porosity modeling for the simulation of complex flow mechanisms in shale reservoirs [J]. Computational Geosciences, 2016, 20(1): 69−91.

[36] LU M, CONNELL L D. A dual-porosity model for gas reservoir flow incorporating adsorption behaviour—part I. Theoretical development and asymptotic analyses[J]. Transport In Porous Media, 2007, 68(2): 153−173.

[37] CONNELL L D, LU M. A dual-porosity model for gas reservoir flow incorporating adsorption behaviour—Part II. Numerical algorithm and example applications[J]. Transport In Porous Media, 2007, 69(2): 139−158.

[38] REN Y C, LIN S C, PEI Q L. Mathematical model of shale gas reservoirs coupled by desorption, stress sensitivity and fractures finite

conductivity[J]. Physical and Numerical Simulation of Geotechnical Engineering, 2017 (26): 27−30.
[39] KARIMI-FARD M, FIROOZABADI A. Numerical simulation of water injection in 2D fractured media using discrete-fracture model[C]//SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana: Society of Petroleum Engineers, 2001.
[40] BACA R G, ARNETT R C, LANGFORD D W. Modelling fluid flow in fractured porous rock masses by finite-element techniques[J]. International Journal for Numerical Methods in Fluids, 1984, 4(4): 337−348.
[41] JUANES R, SAMPER J, MOLINERO J. A general and efficient formulation of fractures and boundary conditions in the finite element method[J]. International Journal for Numerical Methods in Engineering, 2002, 54(12): 1751−1774.
[42] KARIMI-FARD M, DURLOFSKY L J, AZIZ K. An efficient discrete fracture model applicable for general purpose reservoir simulators [C]//SPE Reservoir Simulation Symposium, Houston, Texas: Society of Petroleum Engineers, 2003.
[43] GONG B, KARIMI-FARD M, DURLOFSKY L J. Upscaling discrete fracture characterizations to dual-porosity, dual-permeability models for efficient simulation of flow with strong gravitational effects[J]. SPE Journal, 2008, 13(01): 58−67.
[44] LEE S H, LOUGH M F, JENSEN C L. Hierarchical modeling of flow in naturally fractured formations with multiple length scales[J]. Water Resources Research, 2001, 37(3): 443−455.
[45] MOINFAR A. Development of an efficient embedded discrete fracture model for 3D compositional reservoir simulation in fractured reservoirs[D]. Austin: University of Texas at Austin, 2013.
[46] LI X, ZHANG D, LI S. A multi-continuum multiple flow mechanism simulator for unconventional oil and gas recovery[J]. Journal of Natural Gas Science and Engineering, 2015, 26: 652−669.
[47] FENG Q, XU S, WANG S, et al. A stochastic permeability model for shale gas reservoirs based on embedded discrete fracture model[J]. Earth Science, 2017, 42(8):1301−1313.
[48] XIA Y, ZHAO Q H , YANG L, et al. An efficient hybrid model for fractured-vuggy reservoir based on discrete fracture-vug network model[J]. Journal of Central South University(Science and Technology), 2017, 48:2474−2483.
[49] DAI C, XUE L, WANG W, et al. Analysis of the influencing factors on the well performance in shale gas reservoir[J]. Geofluids, 2017, 1(1):1−12
[50] 吴明录, 丁明才, 姚军, 等.考虑表面扩散的页岩气藏多级压裂水平井数值模拟.西安石油大学学报(自然科学版) [J].2018, 33(3):29−36. [WU M L, DING M C, YAO J, et al. Numerical simulation of multi-stage fracturing horizontal well in shale gas reservoir considering surface diffusion [J]. Journal of Xi'an Shiyou University(Natural Science Edition), 2018, 33(3): 29–36.]
[51] ANTERION F, EYMARD R, KARCHER B. Use of parameter gradients for reservoir history matching[C]//SPE Symposium on Reservoir Simulation, Houston, Texas: Society of Petroleum Engineers, 1989: 339−354.
[52] BISSELL R C, SHARMA Y, KILLOUGH J E. History matching using the method of gradients: Two case studies[C]//SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana: Society of Petroleum Engineers, 1994: 275−290.
[53] JACQUARD P, JAIN C. Permeability distribution from field pressure data[J]. Society of Petroleum Engineers Journal, 1965, 5(4): 281−294.
[54] CHEN W H, GAVALAS G R, SEINFELD J H, et al. A new algorithm for automatic history matching[J]. Society of Petroleum Engineers Journal, 1974, 14(6): 593−608.
[55] CHAVENT G, DUPUY M, LEMMONIER P. History matching by use of optimal theory[J]. Society of Petroleum Engineers Journal, 1975, 15(1): 74−86.
[56] ROMERO C E, CARTER J N. Using genetic algorithms for reservoir characterization [J]. Journal of Petroleum Science and Engineering, 2001, 31(2): 113−123.
[57] SCHULZE-RIEGERT R W, HAASE O, NEKRASSOV A. Combined global and local optimization techniques applied to history matching[C]//SPE Reservoir Simulation Symposium, Houston, Texas: Society of Petroleum Engineers, 2003: 1−10.
[58] PEREZ R, LAREZ C J, PAREDES J E. Evolution strategy algorithm through assisted history matching and well placement optimization to enhance ultimate recovery factor of naturally fractured reservoirs[C]//SPE Reservoir Characterization and Simulation Conference and Exhibition, Abu Dhabi, UAE: Society of Petroleum Engineers, 2013: 1−14.
[59] MASCHIO C, SCHIOZER D J. Bayesian history matching using artificial neural network and Markov Chain Monte Carlo[J]. Journal of Petroleum Science and Engineering, 2014, 123: 62−71.
[60] FOROUD T, SEIFI A, AMINSHAHIDI B. Assisted history matching using artificial neural network based global optimization method – Applications to Brugge field and a fractured Iranian reservoir[J]. Journal of Petroleum Science and Engineering, 2014, 123: 46−61.
[61] MINGCHUAN W, TAIZHONG D, HONG J S, et al. Research progress in reservoir automatic history matching[J]. Science & Technology Review, 2016, 34(18):236−245.
[62] EVENSEN G. Sequential data assimilation with a nonlinear quasi-geostrophic model using Monte Carlo methods to forecast error statistics[J]. Journal of Geophysical Research: Oceans, 1994, 99(C5): 10143−10162.
[63] GEIR E, MANNSETH T, VEFRING E H. Near-well reservoir monitoring through ensemble Kalman filter[C]//SPE/DOE improved oil

recovery symposium, Tulsa, Oklahoma: Society of Petroleum Engineers, 2002.

[64] ZHAO H, LI Y, YAO J, et al. Theoretical research on reservoir closed-loop production management[J]. Science China Technological Sciences, 2011, 54(10):2815−2824.

[65] 王玉斗，李茂辉.集合卡尔曼滤波方法在非线性油藏问题中的应用[J]. 中国石油大学学报(自然科学版). 2010, 34(5):188−192. [WANG Y D, LI M H. Application of ensemble Kalman filter in nonlinear reservoir problem[J]. Journal of China University of Petroleum(Edition of Natural Science), 2010, 34(5):188−192.]

[66] LORENTZEN R J, NAEVDAL G, VALLES B, et al. Analysis of the ensemble Kalman filter for estimation of permeability and porosity in reservoir models[C]//SPE Annual Technical Conference and Exhibition, Dallas, Texas: Society of Petroleum Engineers, 2005.

[67] GALLI A, BEUCHER H, LE Loc'h G, et al. The pros and cons of the truncated Gaussian method[M]//Geostatistical simulations. Dordrecht: Springer, 1994: 217−233.

[68] LE Loc'h G, GALLI A. Truncated plurigaussian method: Theoretical and practical points of view[J]. Geostatistics wollongong, 1997, 96(1): 211−222.

[69] LIU N, OLIVER D S. Automatic history matching of geologic facies[C]//SPE annual technical conference and exhibition, Denver, Colorado: Society of Petroleum Engineers, 2003.

[70] ZHOU H, GÓMEZ-HERNÁNDEZ J J, Franssen H J H, et al. An approach to handling non-Gaussianity of parameters and state variables in ensemble Kalman filtering[J]. Advances in Water Resources, 2011, 34(7):844−864.

[71] AGBALAKA C C, OLIVER D S. Application of the EnKF and localization to automatic history matching of facies distribution and production data[J]. Mathematical Geosciences, 2008, 40(4): 353−374.

[72] ZHAO Y, REYNOLDS A C, LI G. Generating facies maps by assimilating production data and seismic data with the ensemble Kalman filter[C]//SPE Symposium on Improved Oil Recovery, Tulsa, Oklahoma, USA: Society of Petroleum Engineers, 2008.

[73] MORENO D, AANONSEN S I. Stochastic facies modelling using the level set method[C]//EAGE conference on petroleum geostatistics, Cascais, Portugal, 2007.

[74] JAFARPOUR B, MCLAUGHLIN D B. History matching with an ensemble Kalman filter and discrete cosine parameterization[J]. Computational Geosciences, 2008, 12(2): 227−244.

[75] 王玉斗, 何健, 李高明. 基于离散余弦变换的集合Kalman滤波方法对河流相油藏渗透率场的反演. 地球物理学报, 2011, 54(7): 1900−1911. [WANG Y D, HE J, LI G M. Inverse of the fluvial channel reservoir permeability field using ensemble Kalman filter based on discrete cosine transform[J]. Chinese Journal Of Geophysics, 2011, 54(7): 1900−1911.]

[76] DOVERA L, DELLA Rossa E. Ensemble Kalman filter for Gaussian mixture models[C]//EAGE Conference on Petroleum Geostatistics, Cascais, Portugal, 2007.

[77] WEN X H, CHEN W H. Real-time reservoir model updating using ensemble Kalman filter[C]//SPE reservoir simulation symposium, The Woodlands, Texas: Society of Petroleum Engineers, 2005.

[78] GU Y, OLIVER D S. An iterative ensemble Kalman filter for multiphase fluid flow data assimilation[J]. SPE Journal, 2007, 12(04): 438−446.

[79] LU L, ZHANG D. Assisted history matching for fractured reservoirs by use of hough-transform-based parameterization[J]. SPE Journal, 2015, 20(05): 942−961.

[80] LIU X, DAI C, XUE L, et al. Estimation of fracture distribution in a CO_2−EOR system through Ensemble Kalman filter[J]. Greenhouse Gases: Science and Technology, 2018, 8(2): 257−278.

[81] DACHANUWATTANA S, XIA Z, YU W, et al. Application of proxy-based MCMC and EDFM to history match a shale gas condensate well[J]. Journal of Petroleum Science and Engineering, 2018, 167: 486−497.

[82] WARPINSKI N R, MAYERHOFER M, AGARWAL K, et al. Hydraulic-fracture geomechanics and microseismic-mource mechanisms [J]. SPE Journal, 2013, 18(04):766−780.

[83] CIPOLLA C, WENG X, MACK M, et al. Integrating microseismic mapping and complex fracture modeling to characterize fracture complexity[C]//SPE/EAGE European Unconventional Resources Conference & Exhibition From Potential to Production, The Woodlands, Texas, USA, 2012.

[84] ZIMMER U, MAXWELL S C, WALTMAN C K, et al. Microseismic monitoring quality-control (QC) reports as an interpretative tool for nonspecialists[J]. SPE Journal, 2009, 14(04): 737−745.

[85] BO-X Z, ZHOUG W, RUI L, et al. Review of Microseismic monitoring technology research[J]. Progress in Geophysics, 2014, 29(4):1882−1888.

[86] WARPINSKI N, MAYERHOFER M, DAVIS E, et al. Integrating fracture diagnostics for improved microseismic interpretation and stimulation modeling [C]//Unconventional Resources Technology Conference, Denver, Colorado, 25−27 August 2014.

[87] CORNET F H. Study of acoustic and microseismic emissions associated with a hydraulic fracture[C]// Seminar on Geothermal Energy, Brussels, Belgium, 1977.

[88] BENNETT L, CALVEZ J L, SARVER D R R, et al. The source for hydraulic fracture characterization[J]. Oilfield Review, 2005, 17(4): 42−57.

[89] CIPOLLA C L, WILLIAMS M J, WENG X, et al. Hydraulic fracture monitoring to reservoir simulation: Maximizing value[C]//Second EAGE Middle East Tight Gas Reservoirs Workshop, 2010.

[90] MAXWELL S C, URBANCIC T I, Steinsberger N, et al. Microseismic imaging of hydraulic fracture complexity in the Barnett shale[C]//SPE annual technical conference and exhibition, San Antonio, Texas: Society of Petroleum Engineers, 2002.

[91] FISHER M K, HEINZE J R, HARRIS C D, et al. Optimizing horizontal completion techniques in the Barnett shale using microseismic fracture mapping[C]//SPE Annual Technical Conference and Exhibition, Houston, Texas: Society of Petroleum Engineers, 2004.

[92] MAYERHOFER M J, LOLON E, WARPINSKI N R, et al. What is stimulated reservoir volume?[J]. SPE Production & Operations, 2010, 25(01): 89−98.

[93] DAVEY H, DAVIS T. Characterization of unconventional reservoirs through the use of an integrated rock quality index[C]//75th EAGE Conference & Exhibition-Workshops, London, UK, 2013.

[94] SENA A, CASTILLO G, CHESSER K, et al. Seismic reservoir characterition resource shale play:Stress analyisis and sweet discrimination [J]. The Leading Edge, 2011, 30(3):758−764.

[95] LIU S, VALKÓ P P, MCKETTA S, et al. Microseismic closure window better characterizes hydraulic fracture geometry[C]//SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas, USA: Society of Petroleum Engineers, 2016.

[96] XU W, THIERCELIN M J, GANGULY U, et al. Wiremesh: A novel shale fracturing simulator[C]//International Oil and Gas Conference and Exhibition in China, Beijing, China: Society of Petroleum Engineers, 2010.

[97] DERSHOWITZ B, LAPOINTE P, EIBEN T, et al. Integration of discrete feature network methods with conventional simulator approaches[C]//SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana: Society of Petroleum Engineers, 1998.

[98] YU X, RUTLEDGE J, LEANEY S, et al. Discrete fracture network generation using microseismic data from a single monitoring well[C]//Unconventional Resources Technology Conference, San Antonio, Texas, 2016.

[99] KANAMORI H. The energy release in great earthquakes[J]. Journal of Geophysics Research, 1977, 82: 2981−2987.

[100] WILLIAMS-STROUD S C, EISNER L. Stimulated fractured reservoir DFN models calibrated with microseismic source mechanisms [C]//44th US Rock Mechanics Symposium and 5th US-Canada Rock Mechanics Symposium, Salt Lake City, Utah: American Rock Mechanics Association, 2010.

[101] XU W, THIERCALIN M J, WALTON I C. Characterization of hydraulically-induced shale fracture network using an analytical/semi-analytical model[C]//SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana: Society of Petroleum Engineers, 2009.

[102] HU J L, KANG Z H, YUAN L L. Automatic fracture identification using ant tracking in Tahe oilfield[J].Advanced Materials Research, 2014, 962: 556−559.

[103] SHAKIBA M, SEPEHRNOORI K. Using embedded discrete fracture model (EDFM) and microseismic monitoring data to characterize the complex hydraulic fracture networks[C]//SPE annual technical conference and exhibition, Houston, Texas, USA: Society of Petroleum Engineers, 2015.

[104] ZHOU Z , SU Y , WANG W , et al. Integration of microseismic and well production data for fracture network calibration with an L-system and rate transient analysis[J]. Journal of Unconventional Oil and Gas Resources, 2016, 15:113−121.

[105] CLARKSON C R , BEIERLE J J . Integration of microseismic and other post-fracture surveillance with production analysis: A tight gas study[J]. Journal of Natural Gas Science and Engineering, 2011, 3(2):382−401.

[106] YIN J, XIE J, DATTA-GUPTA A, et al. Improved characterization and performance assessment of shale gas wells by integrating stimulated reservoir volume and production data[C]//SPE Eastern Regional Meeting, Columbus, Ohio, USA: Society of Petroleum Engineers, 2011.

[107] XIE J, YANG C, GUPTA N, et al. Integration of shale-gas-production data and microseismic for fracture and reservoir properties with the fast marching method[J]. SPE Journal, 2015, 20(02): 347−359.

[108] WU K, OLSON J E. Simultaneous multifracture treatments: Fully coupled fluid flow and fracture mechanics for horizontal wells[J]. SPE Journal, 2015, 20(02): 337−346.

[109] FAN D, ETTEHADTAVAKKOL A . Semi-analytical modeling of shale gas flow through fractal induced fracture networks with microseismic data[J]. Fuel, 2017, 193:444−459.

[110] PATTERSON R, YU W, WU K. Integration of microseismic data, completion data, and production data to characterize fracture geometry in the Permian Basin[J]. Journal of Natural Gas Science and Engineering, 2018, 56: 62−71.

(编辑 付娟娟)