纯液态 CO_2 压裂非稳态过程数值模拟*

陆友莲[1] 王树众[1] 沈林华[1] 宋振云[2] 李志航[2]
(1. 西安交通大学动力工程多相流国家重点实验室 2. 川庆钻探工程公司长庆石油勘探局工程技术研究院)

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摘 要 为了解纯液态 CO_2 压裂初始井底压力和温度随时间的演化规律, 对压裂液初期非稳态过程进行了数值模拟。从模拟的结果看: 井底液体 CO_2 在压裂的初期会经历较大的温度和压力变化, 液体 CO_2 会因受热而发生相态的变化和体积的膨胀, 最大膨胀幅度达17.2%, 而其重位压头的变化则是引起井底液体 CO_2 压力变化的主要因素。一般在压裂2~5 min后井底温压即可稳定, 稳定后的温度和压力以及稳定所需要的时间主要与压裂液排量、井深有关。如果气井太深, 低温液体 CO_2 会在井筒附近地层造成巨大的温度梯度, 这有可能会引起井筒周围地层热应力的剧烈上升, 从而有利于井筒射孔附近地层的开裂。

主题词 二氧化碳 压裂 压力 温度 数值模拟

CO_2 能增加溶解气驱的能量, 冷却储层, 保证后期进入地层的压裂液所受的施工温度较低。施工结束后, 注入地层中的 CO_2 在温度作用下快速气化, 溶混于水中, 生成的低浓度碳酸可以降低储层黏土的膨胀率, 保持地层的渗透性, 还可解除残留在裂缝壁面上压裂液滤饼的堵塞[1]。与其他压裂液相比, 该压裂液压裂后形成的裂缝具有较高的导流能力和较长的裂缝闭合期, 油气产量要高于其他压裂液裂缝2~4倍, 产油(气)期持续时间也要比其他压裂液裂缝长很多; 同时, 撤压后 CO_2 气化膨胀的增能效应还可以大大缩短压裂液的返排时间[2-5], 可见该压裂技术在开发水敏性低渗透油气藏、高渗透多孔性被堵油气藏和低压油气藏时具有光明的应用前景。

一、问题的描述及数学模型

低温液体 CO_2 在压裂液管路中流动时与地层之间的换热物理模型如图1所示。

图1所示物理模型的地层温度控制方程为:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial y^2}\right) \qquad (1)$$

式中: a 为地层的热扩散率, $a = \frac{k}{\rho c_p} = 2.274\times 10^{-5}$ m^2/s; k 为地层的导热系数, W/(m·K); ρ 为地层的密度, kg/m^3; c_p 为地层的比热容, J/(kg·K)。

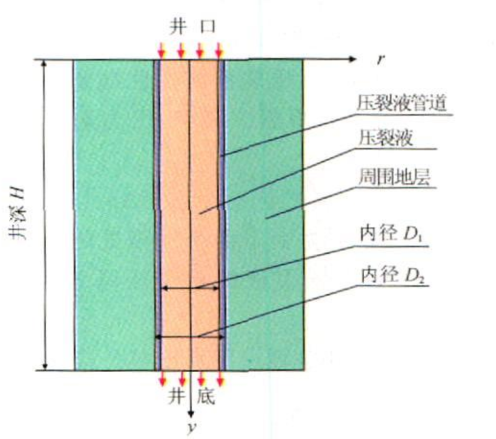

图1 压裂液与地层之间的换热物理模型图

控制方程的初始条件为:

$$T(r, y, t_0) = T(y) = A + By \qquad (2)$$

式中: A、B 分别为地层初始温度分布系数, 分别取30和0.03。

边界条件为:

(1) 井底、井口绝热: $\left.\frac{\partial T}{\partial y}\right|_{y=0,\, y=H} = 0$。

(2) 距管中心无穷远处温度不变, 即

$$T(r, y, t)\,|_{r=\infty} = T(y)$$

本文取 $r = 50$ m 作为无穷远处。

(3) 压裂液管壁处: $\pi D_2 l k \left.\frac{\partial T}{\partial r}\right|_{r=D_2} = \frac{T_f - T_w}{R}$。

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作者简介: 陆友莲, 女, 1982年生, 硕士研究生; 现从事石油天然气增产改造方面研究与应用工作。地址: (710049)陕西省西安市咸宁西路28号。电话: (029)82665157。E-mail: lian3714@163.com

式中：T_f、T_w 分别为管内压裂液温度和与管壁接触处的地层温度，℃；R 为压裂液与地层之间的总热阻，K/W，$\left[R=\frac{\ln(D_2/D_1)}{2k_0\pi l}+\frac{1}{hD_1\pi l}+\frac{R_0}{\pi lD_2}\right]$，$k_0$ 为油管的导热系数，$k_0=50.43$ W/(m·K)；R_0 为压裂液管壁和地层之间的接触面积热阻，取0.04(m^2·K)/W；l 为压裂液管道长度，m；h 为压裂液与油管之间的对流换热系数，W/(m^2·K)。

对流换热系数由Gnielinski公式[6]得到：

$$Nu=0.012(Re^{0.87}-280)Pr^{0.11}\left[1+\left(\frac{d}{l}\right)^{2/3}\right]\left(\frac{Pr}{Pr_w}\right)^{0.11}\qquad(3)$$

式中：Nu 为努塞尔数，$Nu=hl/k_f$；k_f 为压裂液的导热系数，W/(m·K)；Re 为雷诺数；Pr、Pr_w 分别为管内压裂液平均温度的普朗特数和管内压裂液管壁温度的普朗特数；d 为压裂液管道内径，m。

本次研究径向网格步长取0.01 m，纵向网格步长取1 m，时间步长取0.1 s。

在纵向网格上，压裂液的物性都要根据计算出的温度和压力进行更新。其中，压力迭代更新的计算公式为：

$$p_{i+1}=p_i+\Delta p_g-\Delta p_f\qquad(4)$$

式中：p_i、p_{i+1} 分别为上下两个网格处的压力，MPa；Δp_g、Δp_f 分别为压裂液的重位压降和摩擦压降，MPa。

摩擦压降采用达西—维斯巴赫公式：

$$\Delta p_f=\lambda\frac{l}{d}\frac{\rho u^2}{2}\qquad(5)$$

式中：ρ 为压裂液的密度，kg/m^3；u 为管内压裂液平均流速，m/s；λ 为摩擦阻力系数，其值根据文献[4]的试验结果拟合而得。

摩擦阻力系数拟合公式为：

$$\lambda=70.306Re^{-0.5801}\qquad(6)$$

压裂液温度迭代更新的计算式为：

$$G_f c_{pf}(T_f^{i+1}-T_f^i)=\frac{T_w-T_f^i}{R}\qquad(7)$$

式中：G_f 为压裂液的质量流量，kg/s；c_{pf} 为压裂液的比热容，J/(kg·K)；T_f^i、T_f^{i+1} 分别为上、下两个网格处的温度，℃。

CO_2 的物性参数方程详见文献[7]。

二、计算结果及分析

CO_2 压裂技术最大的特点是用液体 CO_2 作为携砂液。由于液体 CO_2 的黏度很低，约为水的1/10，因此其携砂能力较差，压裂时要求有严格的泵送速度和湍流度。实际的压裂作业必须综合考虑压裂液的携砂能力、用量和泵送阻力等，最佳的经济排量为4.77～8.7 m^3/min[4]。排量如果太低，携砂能力会大大下降；排量如果太高，则会增加液体 CO_2 的消耗量及泵送阻力，增加压裂作业的使用费用。一般来说，实际压裂时最好使用≈114.3 mm或≈139.7 mm的压裂液管道[8]。因此，本研究就以这两种管径的压裂液管道来模拟排量为5.0～9.0 m^3/min的压裂初期非稳态过程。模拟结果见图2、表1、表2，与文献[3]给出的实际压裂结果非常吻合。

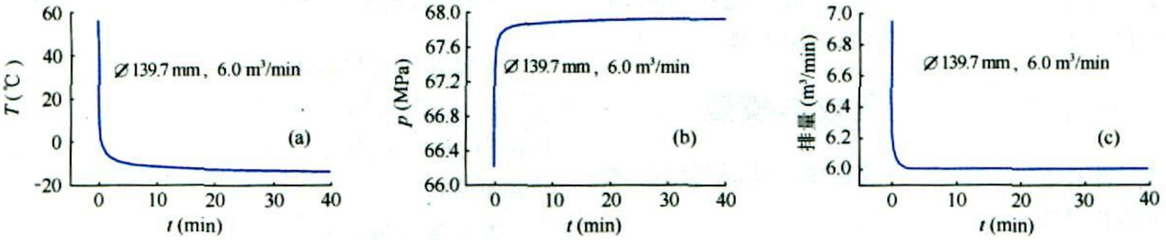

图2　井深2 000 m处压裂液温度、压力、排量随时间的变化图

由图2-a可知，在压裂初始阶段，由于地层温度非常高，压裂液在流动的过程中会被迅速加热，到达井底时压裂液的温度已升高至56 ℃。随着压裂的继续进行，井筒周围地层被迅速冷却，压裂液与地层之间的换热不断减弱，经过2～5 min后，换热过程即可达到稳定。稳定后液体 CO_2 的温度要比注入时偏高5 ℃以上；偏高多少主要和井深及压裂液排量有关（详见表1、2）。由图2-b可以看到，压裂初期的井底压力要明显低于压裂稳定后的井底压力。压裂液流动过程中与地层之间的换热，一方面会引起低温液体 CO_2 密度的下降和重位压头的降低，另一方面还会引起摩擦压降的改变。需要说明的一点是，摩擦压降与液体 CO_2 的体积排量及其黏度有关。液体 CO_2 受热后，体积加速膨胀，同时黏度降低，因此总的摩擦压降可能上升，也可能下降。

图2-c是以实际进口液体 CO_2 排量6.0 m^3/min

表 1　≈114.3 mm 压裂液管道计算结果表

排量 (m^3/min)	井深 (m)	初始状态		稳定状态		稳定时间 (min)
		温度 (℃)	压力 (MPa)	温度 (℃)	压力 (MPa)	
5.0	1 000	28.2	55.51	-17.3	55.97	2.37
	1 500	45.0	58.02	-15.5	58.96	3.38
	2 000	60.0	60.38	-13.5	61.94	4.37
7.0	1 000	20.1	52.20	-18.1	52.46	1.88
	1 500	36.0	53.12	-16.8	53.69	2.65
	2 000	50.6	53.92	-15.3	54.91	3.47
9.0	1 000	14.1	48.40	-18.5	48.51	1.62
	1 500	28.9	47.50	-17.5	47.77	2.25
	2 000	42.7	46.50	-16.4	47.02	2.89

表 2　≈139.7 mm 压裂液管道计算结果表

排量 (m^3/min)	井深 (m)	初始状态		稳定状态		稳定时间 (min)
		温度 (℃)	压力 (MPa)	温度 (℃)	压力 (MPa)	
5.0	1 000	28.5	58.98	-17.1	59.57	2.70
	1 500	45.4	63.18	-15.1	64.37	3.78
	2 000	60.6	67.25	-12.9	69.19	4.90
7.0	1 000	20.5	57.82	-17.9	58.25	2.17
	1 500	36.7	61.49	-16.5	62.40	3.05
	2 000	51.6	65.03	-14.9	66.55	3.98
9.0	1 000	14.7	56.44	-18.4	56.77	1.85
	1 500	29.8	59.46	-17.3	60.16	2.58
	2 000	44.1	62.37	-16.0	63.57	3.38

计算，初始时刻达到 2 000 m 地层处的排量已增加到 6.96 m^3/min，膨胀率高达 17.2%。由于低温液体 CO_2 会引起输运管道的收缩，因此无论在什么样的情况下，都必须使用压力调解采油封隔器，而不能采用应力调解采油封隔器。另外，为了保证井头分离器和采油封隔器不发生位移，必须使用 90—硬膜过氧化氢处理过的丁纳橡胶圈和封装设备。一般来说，压裂作业的失败与否和橡胶圈的使用有很大的关系[4]。

从图 3 可以看到，井筒周围地层的温度梯度会随着井深的增加而迅速上升。在2 000 m处，地层的温度梯度可引起井筒周围地层热应力的剧烈增加，从而会有利于井筒射口附近地层的开裂。

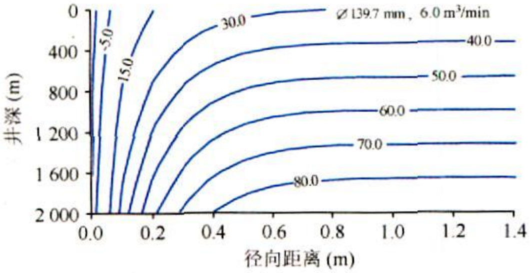

图 3　稳定状态下地层的温度分布状况图

三、结　论

(1) 液体 CO_2 在压裂的初期会经历较大的温度和压力变化，一般在压裂 2～ 5 min 后即可达到稳定，稳定后的温度和压力以及稳定所需要的时间主要和压裂液排量及井深有关。

(2) 压裂初期，受热引起的黏度变化对井底压力的影响要大于受热引起的排量变化的影响；静液柱压头对井底压力的影响要大于摩擦压降的影响；液体 CO_2 的膨胀率高达 17.2%。因此必须使用压力调解采油封隔器和 90—硬膜过氧化氢处理过的丁纳橡胶圈及封装设备。

(3) 如果油井太深，低温液体 CO_2 会造成井筒附近地层巨大的温度梯度，这有可能会引起井筒周围地层热应力的剧烈增加，从而有利于井筒射口附近地层的开裂。

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tem has significant advantages of simple preparation on site, no harm, automatic steering, low fluid loss and retarding, which is applied in the northern oil fields of Kuwait Oil Company (KOC) with a remarkable stimulation effect.

SUBJECT HEADINGS: acidizing, viscosity, activity, additive, mechanism

LIU Yi, born in 1982, is studying for an M. Sc. degree and is mainly engaged in technical research works on stimulation of oil and gas fields.

Add: Drilling & Production Technology Research Institute, PetroChina Jidong Oilfield Company, West Xinhuadong Rd., Tangshan City, Hebei Province 063000, P. R. China

Mobile: + 86-15909753961 6 **E-mail:** liu0yi@163.com

PHASE STATE RESEARCH ON HYDROCARBONS AROUND FRACTURE AFTER CO_2 FRACTURING

WEI Yun-sheng[1], HU Yong-quan[2], ZHANG Xiao-feng[1], RUAN Gang[3], JIA Cheng-ye[3] ([1] Ordos Branch of PetroChina Petroleum Exploration & Development Research Institute; [2] Southwest Petroleum University; [3] PetroChina Dagang Oilfield Company). *NATUR. GAS IND.* VOLUME 28, ISSUE 11, pp. 91-92, 11/25/2008. (ISSN 1000-0976; **In Chinese)**

ABSTRACT: Compared with conventional hydraulic fracturing, CO_2 fracturing has many advantages: in addition to traditional virtues of little filtration, easy flowback and low damage etc., CO_2 can also decrease dew point pressure of hydrocarbons and extract heavily intermediate component condensated easily, which can effectively relieve the condensate oil pollution around fracture caused by change of temperature and pressure in condensate gas reservoirs. It enhances condensate gas recovery and offers a new way to reasonable and effective development of condensate gas reservoirs. A well in the Baimiao condensate gas reservoir, the Zhongyuan oil field, is taken as an example, and a numerical model is formed to research on hydrocarbons phase state and condensate oil saturation of each point at the time of pumping off in CO_2 fracturing when molecule percentage of CO_2 is different. The results indicate that the important reason why CO_2 fracturing is better than conventional hydraulic fracturing is CO_2 gas effect on hydrocarbons phase state in condensate gas, and there is obvious difference among the degrees of effect on hydrocarbons phase state when molecule of CO_2 is different. The results offer theoretical reference to interpret the actual result and optimize gas volume and fracturing scale in condensate gas reservoir fracturing.

SUBJECT HEADINGS: carbon dioxide, condensate gas field, fracture (rock), phase, saturation, Baimiao gas reservoir

WEI Yun-sheng, born in 1979, is studying for a Ph. D degree and is now engaged in studies of oil and gas fields development strategy and supporting techniques.

Add: Ordos Branch of PetroChina Petroleum Exploration & Development Research Institute, No. 20, Xueyuan Rd., Haidian District, Beijing 100083, P. R. China

Tel: + 86-10-6209 3217 **E-mail:** weiyunsheng_1999@163.com

NUMERICAL SIMULATION ON THE INITIAL UNSTABLE STAGES OF LIQUID CO_2 FRACTURING

LU You-lian[1], WANG Shu-zhong[2], SHEN Lin-hua[1], SONG Zhen-yun[2], LI Zhi-hang[2] ([1] State Key Laboratory for Multiphase Flow in Power Engineering, Xi´an Jiaotong University; [2] Technology Engineering Research Institute of CNPC Sichuan-Changqing Drilling & Exploration Corporation). *NATUR. GAS IND.* VOLUME 28, ISSUE 11, pp. 93-95, 11/25/2008. (ISSN 1000-0976; **In Chinese)**

ABSTRACT: The initial unstable stage of pure liquid CO_2 fracturing process was studied numerically to clearly understand the evolvement of bottom hole temperature and pressure. The numerical simulation results show that the bottom hole temperature and pressure will vary considerably at the beginning of fracturing: CO_2 will be heated, which gives rise to the change of its phase from liquid to supercritical, and of its volume maximum expansion up to17.2%; besides, the variation of CO_2 hydrostatic pressure is the main factor influencing the change of the bottom hole pressure. After about 2-5 minutes fracturing the bottom hole temperature and pressure will become stable, which lie on the flux of CO_2 and the well depth. The low-temperature liquid

CO_2 may arouse a great temperature gradient and thermal stress at a relatively deep formation around the oil and gas wellbore, which is beneficial to fracturing.

SUBJECT HEADINGS: carbon dioxide, fracturing, pressure, temperature, numerical simulation

LU You-lian, born in 1982, is studying for an M. Sc. degree, and she is now engaged in studies of EOR measures and application in oil and gas fields.

Add: State Key Laboratory for Multiphase Flow in Power Engineering, Xi′an Jiaotong University, No. 20, West Xianning Rd., Xi′an, Shaanxi Province 710049, P. R. China

Tel: + 86-29-8266 5157 **E-mail:** lian3714@163.com

MATCHING APPLICATION OF DOWNHOLE THROTTLING TECHNOLOGY IN LOW-TEMPERATURE SEPARATION PROCESS

LI Lian-ming[1], TAN Zhong-guo[2], QIAO Ya-bin[2], JIAO Ting-kui[2], LONG Yun-hui[2]([1] School of Energy, China University of Geoseciences • Beijing; [2] The No. 2 Gas Production Plant of PetroChina Changqing Oilfield Company). *NATUR. GAS IND.* VOLUME 28, ISSUE 11, pp.96-98, 11/25/2008. (ISSN 1000-0976; **In Chinese**)

ABSTRACT: The Multiwell heating, throttling refrigeration and low-temperature separation process have been applied in the gas gathering station of the Yulin gas field. Due to the higher wellhead pressure (18-22 MPa), the temperature of incoming gas in a single well directly through the throttling refrigeration would be lower than −20℃ which outreaches the applicable temperature range of normal steel No.20, therefore, it needs to be throttled after being heated so as to attain its temperature demand by low-temperature separation process. On the basis of operation practice of low-temperature separation process in gas gathering stations, in order to solve problems of liquid loading (well bore) and hydrate block (flow line) in multiwell gas gathering stations, the downhole throttling technology was introduced, fundamental principle and gordian technique of the bottom hole choke were studied. Through successful matching application of low-temperature separation process in 14 gas wells, the flow line for a single well was operated under the pressure about 10 to 12 MPa, the incoming gas from a single well was choked directly without heating, the heating furnace was blocked up, not only could the temperature demand of −8 to −18 ℃ be satisfied for the low-temperature separation process, but also the hydrate block of low-productivity gas wells could be removed effectively as well. By means of the matching application, the normal production of low-productivity gas wells and energy saving & declining consumption could be all achieved, methanol rate of injection and gas firing consumption could be reduced, gas production time per year had been raised, and 14 gas wells could save up to 10.7 thousand Yuan per day with obvious economic benefit.

SUBJECT HEADINGS: downhole, throttling, low-temperature separation, matching technology, gas hydrate, block, energy saving

LI Lian-ming (senior engineer), born in 1974, is studying for a Ph. D degree, and is now engaged in studies of geological technology in gas field development.

Add: The No. 2 Gas Production Plant of PetroChina Changqing Oilfield Company, Xisha Economic Development Zone, Yulin City, Shaanxi Province 719000, P.R. China

Tel: + 86-29-6502 158 **E-mail:** llm_cq@petrochina.com.cn

INFLUENCE OF HEAVY HYDROCARBONS ON PHASE BEHAVIOR OF NATURAL GAS

WU Hai-hao[1], SUN Bin-bin[1], SUN Yu[2], Gong Jing[1]([1] Beijing Key Laborarory of Urban Oil and Gas Distribution Technology, China University of Petroleum • Beijing; [2] China Petroleum Pipeline Engineering Corporation). *NATUR. GAS IND.* VOLUME 28, ISSUE 11, pp.99-102, 11/25/2008. (ISSN 1000-0976; **In Chinese**)