垂直裂缝井产量递减曲线研究

杨龙[1]　王晓冬[1]　韩永新[2]

(1.中国地质大学·北京　2.石油勘探开发科学研究院廊坊分院)

杨龙等.垂直裂缝井产量递减曲线研究.天然气工业,2003;23(3):76~79

摘　要　文章利用叠加积分方法,先给出了在封闭油气藏中存在有限导流垂直裂缝的生产井井底压力分布公式,再根据Duhamel原理,计算出垂直裂缝井的弹性产量数据,用不稳态方法预测了单一的、存在有限导流垂直裂缝的气井产量,并利用Stehfest数值反演方法计算得出气井产量递减曲线、累计产量—产量关系曲线,定量讨论了裂缝导流能力、裂缝壁面表皮对气井产量、累计产量的影响,随后举例说明了其应用方法。研究表明,无量纲导流能力、裂缝壁面表皮对产量的影响主要集中在早、中期,当达到晚期拟稳态阶段后,对产量的影响是比较小的。另外,影响水力压裂垂直裂缝井产量的主要因素除了裂缝长度外,还有裂缝的无量纲导流能力,可能有这样的情形,低导流能力的长裂缝和高导流能力的短裂缝等效,从某种程度上说,裂缝的导流能力作用比裂缝缝长更加重要。

主题词　封闭油气藏　产量计算　产量递减　垂直裂缝　裂缝导流能力　数学模型

近年来,在油气藏工程方面,关于垂直裂缝井的研究工作,主要集中于不稳定压力分析方面,如Raghavan(1978年、1993年)、Cinco-ley(1978年、1981年)和Gringarten(1973年、1974年、1975年)、刘慈群等人(1987年、1991年),他们的工作主要集中在油藏—裂缝系统不稳定渗流及试井分析方法的研究。在裂缝井产量分析及预测方面,已有的解析研究结果主要有Prats(1960年)等人给出的稳态椭圆流动近似解;Raymond和Binder(1967年)利用等值渗流阻力法给出了三角裂缝产量预测近似公式,该公式很不准确;Tinsley和Williams(1969年)用电模拟方法研究了部分压开情形下的机理型产量公式;Cinco-ley(1976年)在数值计算有限导流裂缝井壁压力时,顺便给出的等效井径曲线。在压裂设计

现场候凝48 h,钻具承压300 kN,强度满足侧钻要求。

4)侧钻工艺过程。钻具组合:ƒ215.9 mm3A+ƒ172 mm直螺杆+1.75°弯接头+ƒ158.8 mmDc+ƒ158.8 mmDc+ƒ127 mmDP;造斜点位置2 725 m;有线随钻定向。由于地层较硬嘉五段,岩性灰岩,控制钻时200~260 min/m,于井深2 735 m顺利侧出新井眼。该井于2 735 m处出新眼后,由于是水平井,侧钻出去后,采用稳斜钻具钻进,水平井设计剖面采用直—增—稳—增,目前该井已完钻,设计造斜点3 450 m。

认识与体会

截至目前,江汉石油管理局共在海相深井侧钻6口井(新场2井,建69侧平1井,建63侧平1井,建27井侧平1,建41侧平1井,建46侧平1井),积累了一定的海相深井定向侧钻经验,同时取得了以下认识与体会。

(1)分析已钻井实钻资料,对制定合理侧钻方案具有重要意义。

(2)海相中、深井段侧钻,水泥塞强度、侧钻点选择、地层岩性、控制钻时及合适的侧钻工器具是提高侧钻成功率的几个关键因素。

(3)侧钻出新眼后,划眼及修正窗口措施要得当,侧钻时尽量简化钻具组合,缩短定向侧钻时间,确保井下安全。

(收稿日期　2003-01-09　编辑　钟水清)

作者简介:杨龙,1992年毕业于江汉石油学院开发系采油专业,一直从事油气井测试和分析工作,现在中国地质大学(北京)攻读博士学位,发表论文多篇,参加过多项科研项目。地址:(100083)北京市海淀区学院路21号中国地质大学能源地质系博2000级。电话:(010)82320863,13021087541。

中，准确的垂直裂缝井产量预测方法有着重要意义，王鸿勋等(1998 年)在设计计算方法研究中，曾直接引用了上述有关结果。关于垂直裂缝产量的研究总体还缺乏系统的理论推演和应用方法研究工作。

数学模型的建立

圆形封闭地层中，一口带有垂直裂缝的不稳态渗流压力模型如图 1 所示。

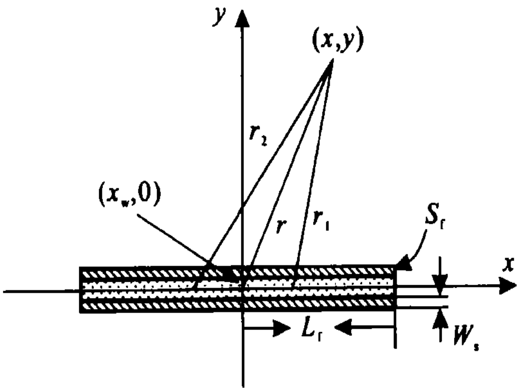

图 1　矩形裂缝模型

在 Laplace 空间中，圆形封闭地层的点汇解式为：

$$p_D(x_D, y_D, s) = \frac{1}{s}\left[K_0\left(\sqrt{s}\sqrt{x_D^2+y_D^2}\right) + \frac{K_1(r_{eD}\sqrt{s})}{I_1(r_{eD}\sqrt{s})}I_0\left(\sqrt{s}\sqrt{x_D^2+y_D^2}\right)\right] \quad (1)$$

垂直裂缝井的井底压力分布公式：

$$p_D(x_D, y_D, s) = \frac{1}{2s}\int_{-1}^{1}q(a,s)\left\{K_0\left[\sqrt{s}\sqrt{(x_D-a)^2+y_D^2}\right] + \frac{K_1(r_{eD}\sqrt{s})}{I_1(r_{eD}\sqrt{s})}I_0\left[\sqrt{s}\sqrt{(x_D-a)^2+y_D^2}\right]\right\}da \quad (2)$$

求解过程中，利用式(3)：

$$p_{wD} - p_{fD}(x_D) = \frac{\pi}{C_{fD}}\left(x_D - \int_0^{x_D}\int_0^{y}q_{fD}(u)\,du\,dv\right) \quad (3)$$

首先计算沿裂缝的流量分布，而后得到井壁压力，再根据 Duhamel 原理，注意到在 Laplace 空间中，井底定产和定压解式有简洁的关系，则对于垂直裂缝井的弹性产量有：

$$Q_D(s) = \frac{1}{s^2 p_{wD}(s)} \quad (4)$$

对于累积产量有：

$$Q_{pD}(s) = \frac{1}{s^3 p_{wD}(s)} \quad (5)$$

在对公式计算中，首先必须解决有关 Bessel 函数积分的计算问题，利用变量变换有以下结果：

$$\int_{-1}^{1}K_0\left[\sqrt{(x_D-a)^2}\,\varepsilon_n\right]da = \frac{1}{\varepsilon_n}\{\pi - [Ki_1(\varepsilon_n + \varepsilon_n x_D) + Ki_1(\varepsilon_n - \varepsilon_n x_D)]\} \quad (6)$$

$$\int_{-1}^{1}I_0\left[\sqrt{(x_D-a)^2}\,\varepsilon_n\right]da = \frac{1}{\varepsilon_n}[Ii_1(\varepsilon_n + \varepsilon_n x_D) + Ii_1(\varepsilon_n - \varepsilon_n x_D)] \quad (7)$$

式中：$Ki_1(z) = \int_z^{\infty}K_0(t)\,dt$

$Ii_1(z) = \int_0^{z}I_0(t)\,dt$

称 $Ki(z)$、$Ii(z)$ 为 Bessel 函数重复积分，将它们展成 chebyshev 多项式，可以获得较好的计算结果。再按照数值反演方法，可快速获得产量递减典型曲线，在选定某一参数，而其它参数相对给定的情形下，计算模型中主要参数的影响，图中展示了给定井底压力下，主要参数变化时，有限导流垂直裂缝井产量递减趋势，图 2 反应了无量纲导流能力变化对产量的影响曲线，由图 2 可以看出，产量随无量纲导流能力的增加而增加，达到拟稳态后，产量变化则趋于一致，图 3 是不同裂缝壁面表皮对产量的影响，随

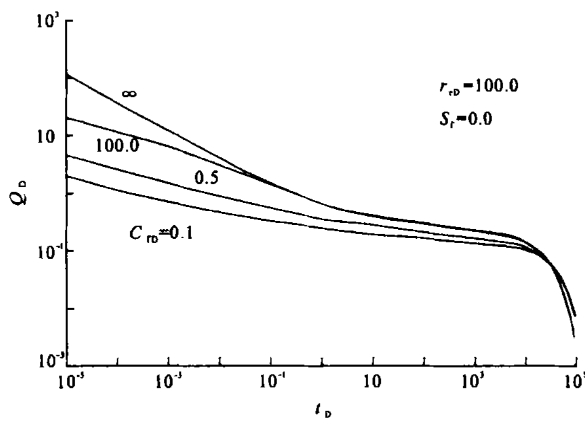

图 2　导流能力对垂直裂缝井产量影响曲线

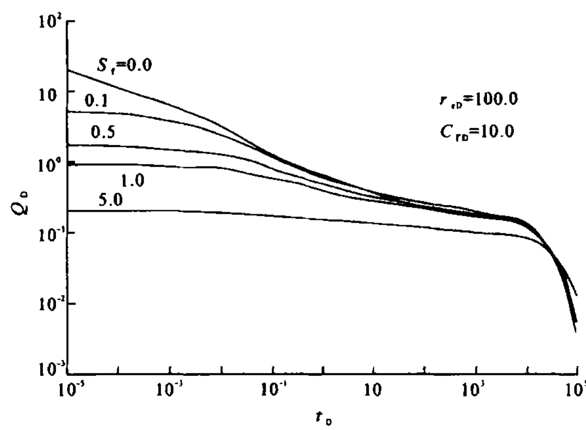

图 3　裂缝壁面表皮对垂直裂缝井产量影响曲线

着裂缝壁面表皮的增大, 产量是降低的, 达到拟稳态后, 产量趋于一致, 图 4、图 5 分别是无量纲导流能力、裂缝壁面表皮对累计产量—产量关系影响曲线, 可以得出下列结论, 无量纲导流能力、裂缝壁面表皮对产量的影响主要集中在中、早期, 当达到拟稳态后, 对产量的影响是比较小的。

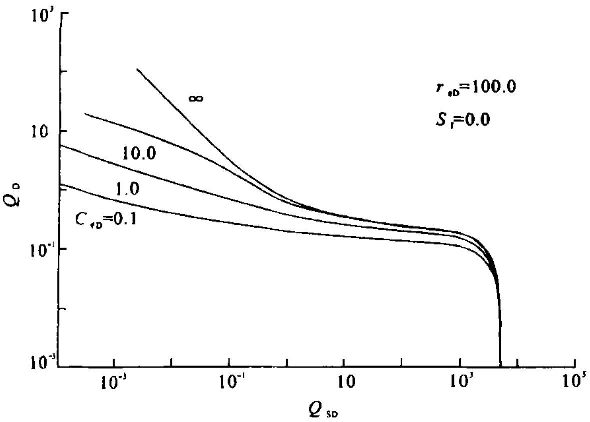

图 4　导流能力对垂直裂缝井累计产量和产量影响曲线

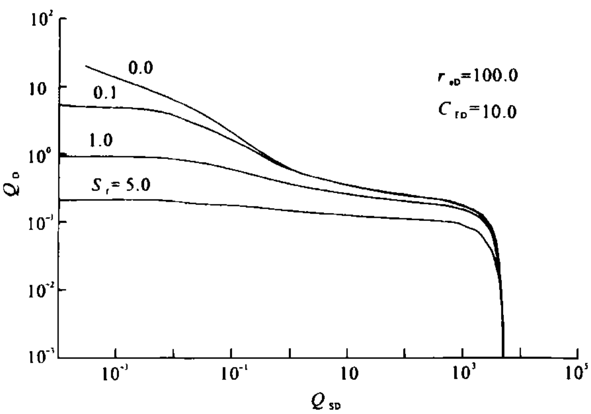

图 5　裂缝壁面表皮对垂直裂缝井累计产量和产量影响曲线

应 用 方 法

下面用一算例说明以上应用方法的正确性。

1. 预测产量

首先要确定无量纲时间、无量纲边界距离、无量纲导流能力和裂缝壁面表皮, 无量纲导流能力和裂缝壁面表皮可以通过不稳定试井得到, 假设该气井生产 150 d。

$$t_D = \frac{3.6Kt}{\varphi\mu_g c_t L_f^2} = \frac{3.6 \times 0.003 \times 150 \times 24}{0.22 \times 0.02 \times 0.017 \times 100^2} = 52.0$$

$$r_{eD} = \frac{r_e}{L_f} = \frac{10000}{100} = 100$$

$$C_{fD}\ \frac{K_f W_f}{KL_f} = 10$$

$$S_f = \frac{\pi W_s}{2L_f}\left(\frac{K}{K_s} - 1\right) = 0.5$$

采用压力平方法定义无量纲压力:

$$p_D = \frac{2.714 \times 10^{-2} T_{sc} Kh(p_i^2 - p^2)}{T p_{sc} \mu_g ZQ} = \frac{78.55Kh(p_i^2 - p^2)}{T\mu_g ZQ}$$

从图 3 可以直接读到无量纲产量为 0.40, 则

$$Q = \frac{78.55KhQ_D(p_i^2 - p^2)}{\mu_g ZT} = \frac{78.55 \times 0.003 \times 20 \times 0.4 \times (30^2 - 25^2)}{0.02 \times 1 \times (273.15 + 80)} = 73.8 \times 10^4 m^3/d$$

2. 计算封闭油藏井的最终采收量

给定废弃产量为 $0.1 \times 10^4 m^3/d$, 有:

$$p_D = \frac{Q\mu_g ZT}{78.55Kh(p_i^2 - p^2)} = 5.45 \times 10^{-5}$$

由直接计算可知, 无量纲累计产量 $Q_{SD} = 8 \times 10^3$, 则:

$$Q_{SD} = \int_0^{t_D} Q_D dt_D = \frac{0.04583 Q_S ZT}{h\varphi c_t L_f^2 (p_i^2 - p^2)}$$

$$Q_D = \frac{Q_{SD} h\varphi c_t L_f^2 (p_i^2 - p_w^2)}{0.04583ZT} = 10167.5 \times 10^8 m^3/d$$

以上针对圆形封闭油气藏和无穷大油气藏展开讨论, 但方法不失一般性, 可以采用拟压力方法代替压力平方方法, 建立和求解矩形气藏, 有平行断层等多种形式的气藏模型, 可按上述步骤预测气井产量。

结　　论

1) 给出了在封闭油气藏中, 用不稳态方法预测单一的、存在有限导流垂直裂缝的气井产量的数学模型、计算方法和应用。研究表明, 影响水力压裂垂直裂缝井的增产效果不只有裂缝长度, 还有裂缝的无量纲导流能力, 会有这样的情形, 低导流能力的长裂缝和高导流能力的短裂缝可能等效, 从某种程度上说, 裂缝的导流能力比缝长更加重要。

2) 由分析可以得出, 无量纲导流能力、裂缝壁面表皮对产量的影响主要集中在中、早期, 当达到拟稳态后, 它们对产量的影响是比较小的。

3) 用 VB6.0 结合 VC++ 6.0 研制了垂直裂缝井产量分析软件, 软件中包括稳态和不稳态两种产量计算方法, 可以单独计算裂缝壁面表皮对产量的定量影响。

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天然气井零液流量气提流动的水动力学模型*

刘 磊　周芳德
(西安交通大学动力工程多相流国家重点实验室)

刘磊等. 天然气井零液流量气提流动的水动力学模型. 天然气工业, 2003; 23(3): 79~ 82

摘 要　文章分别以水、轻油和重油为液相, 研究了天然气井中零液流量气提流动这一特殊气液两相流动现象。提出了零液流量气提流动的两相流水动力学模型, 应用该模型计算了零液流量气提流动的持液率和压力降。模型计算结果与试验结果都表明, 零液流量气提流的持液率随表观气速的增大而单调减小, 而摩擦阻力压力降则不随表观气速的变化呈单调性的变化。尽管零液流量气提流的水动力学特性不同于液体流量不为零的常规气液两相流, 零液流量气提流仍遵循常规气液两相流的水动力学基本关系式。

主题词　气井　流动特性　两相流动　压力降　数学模型

零液流量气提流动是天然气井中一类独特的持液流动现象, 该现象是井筒中由于微量液体长时间连续不断地积存形成了液柱, 而气体流速又不足以将液体带出井筒所致, 表现为井筒中存在两相流气提区, 而井口处的液体流量则近似为零。零液流量气提流动现象使天然气井的底部井段存在持液现象, 重位压降因此而增大, 该现象会严重影响天然气的产出率甚至导致液体填死气井[1]。

鉴于"零液流量"这一特殊条件, 针对液体流量不为零的常规气液两相流所提出的持液率和压力降计算关联式不适用于零液流量气提流动。只有针对"零液流量"这一特殊条件建立相应的流动模型, 才能预测零液流量气提流的流动参数。本文对零液流量气提流建立两相流水动力学模型, 计算结果与不同液体为液相的试验结果比较, 以预测天然气井中零液流量气提流动区的持液率和压力降。

试验研究

试验在内径 75 mm、高 10 m 的垂直管中进行(图 1)。10 m 管长代表天然气井的一段。气体进口处安装止回阀, 先将试验段灌满液体, 而后关闭液体侧阀门, 打开气体侧调节阀, 试验段中即形成零液流量气提流动。流体压力由压力表测量, 总压力降由差压传感器测量。待流动稳定后(不再有液体被气体携带出垂直管试验段), 关闭气体侧阀门, 液体滞留于试验段中。根据液位高度可确定持液率。分别以水、轻油和重油模拟天然气井中的液体。轻油粘度为 5 mPa•s, 重油粘度为 20 mPa•s。气体为空气,

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(收稿日期　2003- 01- 18　编辑　韩晓渝)

* 本文为国家自然科学基金项目(No. 50206016), 由教育部留学回国人员基金资助。

作者简介: 刘磊, 1967 年生, 副教授, 博士, 主要从事多相流动及其测量技术的研究。地址: (710049) 陕西省西安市。电话: (029) 2668767。

fect of the bit dip. So, they can control deviation and improve the bit speed. But they haven't the ability to resist the deviation force caused by the formation because of the inside mechanics properties of the drilling tools assemble. Aiming to the steep structures and the formations with strong deviating force, they can't guarantee to control deviation. To solve the problem of deviation control and fast drilling, besides effective controlling the side force of the drilling tools and the bit dip, enough ability should be obtained to resist the deviating force of the formations. The 3 factors must be considered at the same time and coordinated each other, then the problems of deviation control and fast drilling can be solved practically in the steep structures and the formations with strong deviating force.

SUBJECT HEADINGS: Straight well, Drilling technique, Deviation control, Theoritical model, Bottom hole assembly

Sun Kui *(engineer)*, born in 1967, and is the vice general geologist of Shallow Sea Petroleum Development Com. Add: Panjin, Liaoning (124010), China Tel: (0427) 7805626

MODEL OF TEMPERATURE DROP MECHANISM WHEN GAS FLOWING THROUGH CHOKES*

Li Yingchuan and Hu Shunqu (Southwest Petroleum Institute) ; and Guo Chunqiu (Research Institute of Exploration and Development, PCL). *NATUR. GAS IND.* v. 23, no. 3, pp. 70~ 72, 5/25/2003. (ISSN1000- 0976; **In Chinese)**

ABSTRACT: Based on energy conservation theory and Van Der Waals' s mixed rule, a mathematical model is derived. The model describes the phase equilibrium process with Peng-Robinson equation when gas flowing through chokes. Data acquired from the Brown enthalpy-entropy diagram was used to calculate the real cases, comparing the results come from the model with the data from the enthalpy-entropy diagram. Under the conditions of gas' s density from 0.6 to 1.0, temperature from 93.3 to 371.1℃ and pressure from 0.0344 to 68.95 MPa, the results acquired from the model matched well with the values from the Brown enthalpy-entropy diagram. The average error was − 0.21% and the absolute average error of them was 0.55%. Therefore, it proved that the model is correct and has wide applicable scope. Comparing with the Brown enthalpy-entropy diagram, the computer program of the model has the advantages such as quick calculation, convenient application and good adaptability, and provides an important tool for the engineering design of the gas recovery and transportation and the production dynamic analysis such as prediction and prevention of the gas hydrate.

SUBJECT HEADINGS: Natural gas, Throttle, Temperature drop when gas flowing through chokes, Phase equilibrium, Mathematical model

Li Yingchuan *(professor)*, born in 1951. Add: Nanchong, Sichuan (637001), China Tel: (0817) 2642091 E-mail: liyc@swpi.edu.cn

DIRECTIONAL SIDETRACKING TECHNIQUES OF MARINE DEEP WELLS IN YUDONG AREA OF WEST HUBEI PROVINCE*

He Kaiping (Jianghan Oil Field Branch, Sinopec). *NATUR. GAS IND.* v. 23, no. 3, pp. 73~ 76, 5/25/2003. (ISSN1000- 0976; **In Chinese)**

ABSTRACT: The geological structures are complicated in Yudong area of west Hubei province. The sidetracking is difficult. It is very important how to rehabilitated the productivity of the old wells with the new sidetracking techniques. Based on the geological and structural features in Yudong area of West Hubei province, the article analyzed the characteristics and the deficiencies of the sidetracking techniques of marine deep wells. Using the real cases of 2 wells, the article described the practical application of 2 sidetracking types both open hole sidetracking and casing well sidetracking in the fields, and provided some ideas.

SUBJECT HEADINGS: Deep well, Sidetracking, Technique, Old well, Yudong area of west Hubei province

He Kaiping *(Doctor, senior engineer)*, born in 1956, and is the vice general engineer of Jianghan Oil Field Branch, Sinopec. Add: Qianjiang, Hubei (433124), China Tel: (0728) 6509580

STUDY OF PRODUCTION DECLINE CURVE FOR WELLS WITH VERTICAL FRACTURES*

Yanglong and Wang Xiaodong (China University of Geosciences, Beijing), and Han Yongxin (Langfang Branch of Research Institute of Petroleum Exploration and Development). *NATUR. GAS IND.* v. 23, no. 3, pp. 76~ 79, 5/25/2003. (ISSN1000 - 0976; **In Chinese)**

ABSTRACT: Using stacking integration, the article derived the equation of buttonhole pressure distribution of producing wells limited diverting vertical fractures in closed oil and gas reservoirs, calculated the elastic production date of wells with vertical fractures according to Duhamel principle, estimated the production of each well with limited diverting vertical fractures by means of transient testing method, made the production decline curve and the cumulative production versus production curve by means of Stehfest numerical inversion method, and discussed the influence of fracture conductivity and fracture skin on the production and the cumulative production of a gas well quantitatively then explained the application with examples. The study shows the influence of the dimensionless conductivity and the fracture skin on the production mainly happens in the early and medium period, and the influence is a little in the late period when the pseudosteady state appears. Otherwise, the major factors to influence the production of the fractured well with vertical fractures are the fractures dimensionless conductivity as well as the fracture lengths. Maybe it happens that the low conductivity with long fractures is equal to the high conductivity with short fractures. In a sense, the effect of fracture conductivity is more important than that of fracture lengths.

SUBJECT HEADINGS: Closed reservoir, Production calculation, Production decline, Vertical fracture, Fracture conductivity, Mathematical model

Yanglong is studying for doctor degree. Add: 21 Xueyuan Rd., Beijing (100083), China Tel: (010) 82320863 Cell: 13021087541

A HYDRODYNAMIC MODEL FOR GAS-LIFTING FLOW IN A GAS WELL WITH LIQUID FLOW RATE BEING ZERO*

Liu Lei, Zhou Fangde (National Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University). *NATUR. GAS IND.* v. 23, no. 3, pp. 79~ 82, 5/25/2003. (ISSN1000- 0976; **In Chinese)**

Abstract: Taking water, light oil, and heavy oil as the liquid phase, the article studied the special phenomenon of gas-liquid two-phase flow in a gas well with liquid flow rate being zero, and developed a hydrodynamic model of gas-lifting 2 phases flow with liquid flow rate being zero. Using the model, the liquid holding efficiency and pressure drop of gas-lifting flow with liquid flow rate being zero was calculated. Both the results calculated from the model and the results from the experience indicate the liquid holding efficiency of gas-lifting flow with liquid flow rate being zero decreases consistently as the increase of superficial gas velocity, while the frictional pressure drop does not change as the change of superficial gas velocity. Although the hydrodynamic features of gas-lifting flow with liquid flow rate being zero are different from the general gas-liquid two-phase flow, the gas-lifting flow with liquid flow rate being zero also follows the basic hydrodynamic principles of the general gas-liquid two-phase flow.

SUBJECT HEADINGS: Gas well, Flow propertry, Two-phase flow, Pressure drop, Mathematical model

Liu Lei (*assistant professor, Doctor*), born in 1967. Add: Xi' an, Shanxi (710094), China Tel: (029) 2668767

MODEL STUDY OF MULTI-COMPONENT GAS ADSORPTION THEORY IN RESERVOIR POROUS MEDIA*

Ou Chenghua (Southwest Petroleum Institute). *NATUR. GAS IND.* v. 23, no. 3, pp. 82~ 84, 5/25/2003. (ISSN1000- 0976; **In Chinese)**

ABSTRACT: Almost all gases are multi-component in reservoir porous media. So the question of gas adsorption in reservoir porous media can be solved only with the multi-component model. Based on the 10 multi-component gas adsorption model of porous media which are used widely in the chemical industry, the applicability study of gas adsorption of reservoir porous model has conducted integrating the parameter values of the fitted single component model and the experiment data of multi-component gas isothermal adsorption in the relative reservoir porous media. The results indicate: ① Wilson VSM model can be used to correlate the mixed gas adsorption of reservoir porous media when the number of the gas components is small. But to facilitate the calculation, the DSL model will be the optimal choice; ② The adsorption data calculated by FHVSM model have the least difference with the data from the reservoir porous media when the number of the gas components is big; ③ Since the number of gas components of gas reservoir is usually above 3, better results will be obtained when FHVSM model is used for the adsorption calculation of real gas reservoir.

SUBJECT HEADINGS; Reservoir, Core, Multi-component mixture, Adsorption, Mathematical model, Calculation

Ou Chenghua (*Doctor, instructor*) born in 1971. Add: Nanchong, Sichuan (637001), China Tel: (0817) 2642942 E-mail: chomm@163.com

GAS-SOLID-HEAT COUPLING MATHEMATICAL MODEL OF GAS PERCOLATION FLOW IN ELASTIC GAS RESERVOIR

Wang Ziming, Jiang Tongwen and Song Wenjie (Talimu Oil Field Branch, PCL) and Du Zhimin (Southwest Petroleum Institute). *NATUR. GAS IND.* v. 23, no. 3, pp. 85 ~ 87, 5/25/2003. (ISSN1000-0976; **In Chinese)**

ABSTRACT: A new gas-solid-heat coupling mathematical model taking the gas pressure, rock solid particle displacement and absolute temperature as the basic varibles was set up by applying comprehensively the theories of percolation mechanics rock mechanics and thermodynamics. Let it be supposed in the model that the rock matrixes in gas reservoir may be deformed and the heat can be freely transferred according to thermodynamic laws and the model includes the fully coupling gas percolation, temperature field and rock deformation equations. The model established by the authors, which realizes the real couplying among percolation flow, rock deformation and temperature change in gas reservoir and can more objectively reflect the gas reservoir reality by contrast to the existent gas reservoir percolation models, has developed the conventional gas reservoir percolation theory and fluid-solid couplying mechanical theory and can be widely applied to many realms of gas reservoir engineering.

SUBJECT HEADINGS: Gas reservoir, Elastic media, Rock deformation, Percolation model, Thermal simulation, Coupling, Mathematical model

Wang Ziming, born in 1973, is a postdoctoral researcher. Add: Ku' erlei, Xinjiang (841000), China Tel: (0996) 2174795

DERIVATION AND CALCULATION OF A MULTIPARAMETER MODEL OF FRACTURING FLUID FILTRATION IN DUAL POROSITY MEDIA

Fu Yongqiang, Guo Jianchun and Zhao Jinzhou (Southwest Petroleum Institute) and Min Hang (Northwest Bureau of Petroleum Geology). *NATUR. GAS IND.* v. 23, no. 3, pp. 88~ 91, 5/25/