

对气井井筒压力温度分析的新认识

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摘要 文章提出气井在井筒流动的稳定性应分为质量稳定和热力稳定的问题。综合二维径向多阶段不稳定热扩散分析解, 和垂直井(斜井)管流质量守恒、动量守恒、能量守恒、状态方程, 给出了预测井筒流动、地层热扩散双重不稳定规律的数学模型和数值解法。以新疆柯克亚气田柯深1井进行了实例分析, 发现传统的考虑井筒稳定流动方法计算结果, 由于忽略了井筒中的热力不稳定变化过程, 压力和温度明显高于本文方法的计算结果。以本文方法对比计算不同产气量的情况, 结果符合一般认识。由于岩石热扩散系数很小, 气井工作制度的变化会引起气井长期的热力不稳定, 对于气井井筒不稳定动态的模拟在气井产能评价、动态分析等方面具有重要的意义。

关键词 压力 温度 不稳定流动 稳定流动 气井 叠加原理

井筒稳定流动应该分为两个层次: 流量稳定和热力稳定。流量稳定比较容易满足, 在新的工作制度下几个小时内便可以达到。热力稳定比较困难, 因为在地层中, 热力波的传播速度是很慢的, 一般只有普通油层中压力波传播速度的 10^{-6} 倍。对于气井来说, 井筒压力与温度是密切相关的。对于气井压力、温度分析的正确与否, 直接影响到气井产能评价、生产系统动态分析和生产设施的优化, 因此, 对于气井井筒动态的研究一直受到广泛的关注。研究气井井筒压力温度动态的方法有三类: 第一类, Ramey 方法, 合理地分离压力, 只研究井筒中气体的温度分布。第二类, 井筒整体或分段温度平均的方法, 推导出井底压力的迭代试算公式, 如著名的 Culender-Smith 方法。第三类, 较为复杂, 但更为合理, 考虑井筒中的流动是稳定流动, 而地层中的传热过程为不稳定的, 利用稳定热源精确数学解构造与时间相关的散热关系表达式代入到能量守恒方程中去, 实现压力与温度的计算耦合^[1,2]。以上三类方法, 均只考虑到井筒中的稳定流动。而实际情况是, 井筒中的流动常常是不稳定的。基于此, 本文考虑井筒中流动、地层中传热均是不稳定的。建立了相应的数学模型, 并给出了数值算法。该方法能计算任意流动状况、任意时刻、沿井筒的压力温度分布。用塔里木气井进行实例分析, 验证了方法的准确性。

多阶段不稳定热扩散

设有稳定的热源, 单位长度的产热量为 Q , 则, 此热源在平面无穷大介质中产生的温度分布可用如下数学模型来描述^[3]:

$$T = T_i + \frac{Q}{\pi^2 k} I(r_D, t_D) \quad (1)$$

$$I(r_D, t_D) = \int_0^\infty \frac{1 - e^{-u^2 t_D}}{u^2} \frac{Y_1(u) J_0(ur_D) - J_1(u) Y_0(ur_D)}{J_1^2(u) + Y_1^2(u)} du$$

其中, $r_D = r/r_w$, $t_D = \alpha t/r_w^2$ 。设有不同的阶段, 变热流量情况下, 根据叠加原理, 有

$$T = T_i + \frac{1}{\pi^2 k} \sum_{j=1}^n (Q_j - Q_{j-1}) I(r_D, t_{Dj}) \quad (2)$$

$Q_0 = 0$, $t_0 = 0$, $t_{Dj} = \frac{\alpha(t - t_{j-1})}{r_w^2}$ 。在井筒处, $r_D = 1$, 温度 T_{wb} 可以表示如下:

$$T_{wb} = T_i + \beta + \frac{1}{\pi^2 k} Q_n I_n, I_j = I(1, t_{Dj}), \beta = \frac{1}{\pi^2 k} \sum_{j=1}^{n-1} Q_j (I_j - I_{j-1}) \quad (3)$$

由于, $Q_n = 2\pi r_{ti} U_{ti} (T_{wb} - T)$ 联立上式, 可解得作为井筒中流体函数的热流量:

$$Q_n = \frac{\beta - (T - T_i) \pi^2 k}{\phi - I_n}, \phi = \frac{\pi k}{2 r_{ti} U_{ti}} \quad (4)$$

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井筒不稳定与地层不稳定的耦合 数值解法

气体自井底而上运动,遵循质量守恒、动量守恒和能量守恒,同时,气体还遵循状态方程。对以上 4 式关于位置 x 求导,得^[2]

$$\begin{cases} \frac{d\rho}{dx} = \frac{-\frac{RZ}{c_p M} (Q/w - g\sin\theta) + \frac{f\rho v |v|}{2d} - \rho g\sin\theta}{v^2 - \left(\frac{RZv^2}{c_p M} + \frac{RZT}{M} \right)} \\ \frac{dp}{dx} = \rho g\sin\theta - \frac{f\rho v |v|}{2d} + v^2 \frac{d\rho}{dx} \\ \frac{dT}{dx} = g\sin\theta + \frac{v^2}{\rho} \frac{d\rho}{dx} - Q/w / c_p \\ \frac{dv}{dx} = -\frac{v}{\rho} \frac{d\rho}{dx} \end{cases} \quad (5)$$

笔者注意到,对于任一时间步,在时间离散点上 $Q = Q_n$,是时间、位置的函数,也与 $j = 1, 2, \dots, n-1$ 时刻的换热量有关,也就是即考虑了地层不稳定热扩散也考虑了井筒中不稳定的流动问题。这是本文方法与其它方法的最主要不同之处。上式可以采用标准的常微分方程组解法求解。不再赘述。方法也要求在计算完当前时间步后,存储沿井筒方向上所有点的换热量。

算 例

气井井身结构以柯深 1^[2]井为例,只考虑油层套管。气体压缩因子、定压比热可以根据塔里木盆地的典型气体组成计算。在油管中气体处于高速流动,雷诺数很大,强制对流换热系数很大,因此,可以忽略掉这一部分热阻。油套环空内气体的对流换热属于小空间对流换热,取 $6.5 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ 。

模拟生产 30 d 的情况,对比考虑井筒热力稳定流动情况与热力不稳定情况下井口计算结果。发现不稳定态的计算结果压力、温度均较稳态的要低。特别是温度,不稳态的要低 20 左右。如此大的差距说明,在气井的工作制度进行调整时,如需要考虑调整后的井筒的短期动态,用不稳态的方法来研究会引起较大的误差。对比两种情况,还可以发现,不稳态方法计算的井口压力、温度上升的较稳态方法的要快,这是肯定的,因为一种工作制度下,当时间趋向于无穷大时,不稳态的解和稳定解应当近似相等。对气井产量分别为 $30 \times 10^4 \text{ m}^3$ 、 $60 \times 10^4 \text{ m}^3$ 和 $120 \times 10^4 \text{ m}^3$ 的情况进行了模拟。对比分析井口气体密度、压力、温度和流动速度的变化。首先,对于同一个产量,随时间增加,密度降低,而压力、温度、和流速全部增加。由于井筒气体对周围地层持续加

热,套管外地层温度升高,流动热损失减小,井口压力和温度升高是必然的。温度增加的幅度大于压力升高的幅度,根据状态方程,于是有密度降低;此时,保持质量流速不变,必然线速度增加。其次,对于不同的产量,随产量增加,井口气体密度、压力减小;温度、线速度增加。随产量增加,气体流动线速度必然增加,井口温度增加是由于从井底携带的热量较多,压力降低是由于摩擦阻力增加;由此必然导致井口的密度降低。这是符合我们对井筒流动规律的认识的。

结 论

将井筒中流动规律划分成两个不同的层次,特别是针对井筒中的热力不稳定,建立了数学分析模型。通过比较不稳定解和稳定解的分析结果,发现两种解之间存在着较大的差异。说明,传统的将井筒中流动处理成流量和热力双重稳定的方法会引起较大的偏差。由于本文提出的气井井筒温度压力不稳定模拟的方法同时考虑到了井筒中和地层中双重热力不稳定,在研究气井工作制度变化后的井筒温度压力显然具有前人方法无法达到的精度。本文的对比研究同时也发展了我们对气井井筒行为的认识。该方法考虑了油井的斜度,不但适用于直井,也适用于斜井。

符 号 说 明

T 为温度, K; T_i 为初始温度, K; T_{wb} 为井筒处温度, K; Q 为单位长度换热量, J/m; r 为径向距离, m; r_D 为无因次半径, 无量纲; r_w 为井筒半径, m; t_D 为无因次时间, 无量纲; r_{ti} 为油管内径, m; U_{ti} 为总传热系数, $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$; α 为地层热扩散系数, m^2/s ; k 为地层热导率, $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$; ρ 为井流体物密度, $\text{kg} \cdot \text{m}^{-3}$; R 为气体常数, 等于 $8.3414 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{kmol}^{-1}$; θ 为油井斜度, ($^\circ$); f 为摩擦系数; v 为线速度, $\text{m} \cdot \text{s}^{-1}$; Z 压缩因子; c_p 为定压比热, $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$; M 为气体分子量; d 为油管直径, m; w 为质量流量, $\text{kg} \cdot \text{s}^{-1}$; p 为压力, MPa; x 为位置, m; J_0 、 J_1 为第一类零阶、一阶 Bessel 函数; Y_0 、 Y_1 为第二类零阶、一阶 Bessel 函数。

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West Oil and Gas Field Branch , PCL). *NATUR. GAS IND.* v. 23 , no. 6 , pp. 79 ~ 81 , 11/ 25/ 2003. (ISSN1000 - 0976 ; **In Chinese**)

ABSTRACT: Penglaizhen Formation gas reservoirs of Jurassic in West Sichuan Basin belong in the shallow low-permeability sandstone ones and their reservoir characteristics and damage mechanisms are of typicalness and representativeness in the congeneric gas reservoirs in China. Their reservoir damage mechanisms and degrees were systematically discussed and evaluated by the authors by use of modern core analysis means and a series of simulating experiments. Through studying it is shown that the principal damage mechanism of Penglaizhen Formation gas reservoirs is water locking damage besides which there are still relatively strong alkaline sensitivity , water sensitivity and fracture stress sensitivity and it is also expressed as the water locking damage of the filtrate of working fluid and its solid intrusion damage in the processes of drilling and completing. Finally , relevant suggestions for protecting reservoir from damage are proposed in the paper.

SUBJECT HEADINGS: West Sichuan , Penglaizhen Formation , Low-permeability sandstone , Gas reservoir , Damage , Protection

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HYDRAULIC RESEARCH ON SURFACE FLOW PROCESS PROTECTION AS FRACTURING PROPPANT BACKFLOW

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ABSTRACT: In the process of hydrofracturing , the change of pressure gradient in fractures will cause the fracturing proppant backflow , by which the surface flow process may be seriously damaged because of washout. On the basis of understanding many kinds of surface flow process protection measures , a method of gravitational sand-settling at the high pressure-low speed section of choke upstream is put forward in the paper

through studying by use of hydraulic method. In addition , the design thought and principle of sand-grain catcher (a device for separating solids effectively) are introduced also. The analogue experimental results of the device show that the proppants in both natural gas and sand-carried fluids can be removed by applying such a method , thus protecting the surface flow process efficiently.

SUBJECT HEADINGS: Hydraulic fracturing , Proppant , Washout , Surface flow process , Hydraulics , Sand-grain catcher

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TECHNIQUES OF TREATING SERIOUSLY LOST CIRCULATIONS IN NORTHEAST SICHUAN

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ABSTRACT: The complicatedly and seriously lost circulations in Northeast Sichuan are mainly composed of the lost circulation in large fractures or solution cavities and the one along a long low-pressure interval , etc. Although the number of the seriously lost circulations made up only 10 % ~ 20 % of that of the total lost circulations , the losses caused by them accounted for more than 50 % of the whole lost circulation losses. The types and treatment techniques of the seriously lost circulations in Northeast Sichuan are summarized in the paper , which may give a reference to treating similar lost circulations in the future.

SUBJECT HEADINGS: Sichuan , Northwest , Lost circulation , Loss circulation control

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NEW IDEA FOR BOREHOLE PRESSURE AND TEMPERATURE ANALYSIS OF GAS WELLS¹⁾

Liao Xinwei , Liu Liming (Petroleum University , Beijing)). *NATUR. GAS IND.* v. 23 , no. 6 , pp.

86 ~ 87 , 11/ 25/ 2003. (ISSN1000 - 0976 ; **In Chinese**)

ABSTRACT:The article points out the gas flow stability in the borehole should be divided into quality stability and thermal stability. Integrating the analysis solution of unsteady thermo-diffusion of 2-D radial multi-stages with quality conservation , momentum conservation ,energy conservation ,and state equation of vertical (or deviated) well conductor flow ,the article provides the mathematical model and numeral solution of dual unsteady law to predict borehole flow and formation thermo-diffusion. Taking well Keshen 1 in Kekeya gas field ,Xinjiang as a real example ,it is found that the pressure and temperature calculated by the traditional method ,considering borehole stationary flow , is obviously higher than that calculated by above-mentioned method because the traditional method omits the thermal unsteady variation in the borehole. The results calculated by the above-mentioned method under different gas productions couple with the real situation. Since the thermo-diffusion coefficient of rocks is small ,the working system changing of gas wells will cause long thermal instability of the wells. The dynamic modeling of borehole instability is very useful to the productivity evaluation ,performance analysis of gas wells ,and so on.

SUBJECT HEADINGS:Pressure , Temperature , Unsteady state flow , Stationary flow , Gas well , Stacking principle

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VISCO-ELASTIC PROPERTY SOLID MODEL AND FINITE ELEMENT ANALYSIS FOR EVAPORATE BED CREEP¹⁾

He Kaiping (Jiangnan Petroleum Administration) . *NATURAL GAS IND.* v. 23 ,no. 6 ,pp. 88 ~ 90 , 11/ 25/ 2003. (ISSN1000 - 0976 ; **In Chinese**)

ABSTRACT:Regarding evaporate beds as linear Maxwell solid ,the mechanical model of viscoelastic property is built for plain strain. Using model identifying theory and finite element method ,with real-surveying the caliper variation in different periods for well Wang 78 - 1 of Jiangnan oil field ,the relationship between evaporate bed creep and time ,the stress distribution of the casing under uniform and non-uniform load ,and the influence of casing defects (out of roundness and inhomogeneity) on the casing stress are studied. The results provide quantitative

reference for engineering practice and have high value for expansion and application.

SUBJECT HEADINGS:Evaporate bed ,Background equation ,Casing ,Viscoelastic property ,Model ,Finite element

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NEW PROGRESS OF DOWN HOLE BOOSTING RESEARCH¹⁾

Xiong Jiyou ,Fu Jianhong (Southwest Petroleum Institute) . *NATURAL GAS IND.* v. 23 ,no. 6 ,pp. 91 ~ 93 ,11/ 25/ 2003. (ISSN1000 - 0976 ; **In Chinese**)

ABSTRACT:High pressure jet to crack rocks for assisting drilling has always been an important research subject explored by the well drilling sector. The article classifies the boosting methods which create high pressure jet flow ,and introduces two methods and principle for down-hole boosting ,which are down-hole mechanical boosting method and down-hole hydraulic boosting method. The article mainly describes the principle , method , and the preliminary research results of down-hole hydraulic boosting ,which establish the theoretical base to study the down-hole hydraulic booster.

SUBJECT HEADINGS:Well drilling ,Down-hole ,Booster , Hydraulic boosting ,Research

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INFLUENCE OF CASING INNER WALL BEARING ON RESISTING INNER PRESSURE PERFORMANCE¹⁾

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ABSTRACT:With plastic-elasticity finite element method , the finite element mechanic model of casing is established. The clear definition of the wear allowance and the strength coefficient of resisting inner pressure are made. The strength coefficient of resisting inner pressure with different wearing size of casing inner wall is analyzed and calculated. It is derived that the casing strength of resisting inner pressure vs. the wearing size of