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油管掺液稠油泵井筒流体温度分布计算

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摘要:根据传热学和能量平衡原理,考虑环空产出液与油管掺入液及地层之间的双重热传导作用,同时考虑了由流体相变导致的焦耳-汤姆森效应,建立了稠油泵井筒流体温度分布数学模型,并研究了温度分布随时间的变化规律。编制了计算程序,该程序能用于计算任意生产时间及井筒深度下掺入液及产出液的温度。计算结果表明,在一定条件下,生产时间及焦耳-汤姆森效应对井筒温度分布有明显的影响。

关键词:稠油泵;温度分布;焦耳-汤姆森效应;时间函数;数学模型

中图分类号:TE 355.5　　**文献标识码**:A

1　问题的提出

油管掺液稠油泵是一种通过油管掺液、油套环空产出而进行井筒降粘的新型抽油泵,井筒流体温度分布对其工作状况影响较大。它由上、下两个不同直径的抽吸泵组成,上冲程中上泵腔通过油管吸进地面掺入液,下泵腔吸进地层液;下冲程中上泵腔内的掺入液进入下泵腔,与地层液混合后由排出凡尔排进环空中,稠油泵井筒结构如图 1 所示。上、下两个凡尔的顺利打开与关闭是稠油泵正常工作的关键,而对其影响较大的是流体粘度及温度,因此,准确的井筒温度分布计算是油管掺液稠油泵工作条件与工作参数设置及整个生产系统优化的重要基础。以往的井筒温度分布计算因未考虑流体相变引起的焦耳-汤姆森效应而与实际值存在偏差,井筒温度分布随着生产时间也是不断变化的。笔者根据传热理论同时考虑这些因素,建立油管掺液、环空产出情况下的稠油泵井筒温度分布计算模型。

2　井筒流体温度分布模型的建立

油管掺液稠油泵生产系统中,油管掺入液与地层产出液在泵内混合后通过油套环空产出到地面。泵下井筒内流体与地层间的热交换为热传导过程。泵上部分井筒内的流体热交换过程比较复杂,环空产出液不但通过油管与掺入液发生热交换,而且通过套管和水泥环与地层岩石发生热交换。建立泵下井筒流体的温度分布模型,得到地层产出液在泵入口处的温度,作为泵上部分温度分布模型的一个边界条件,然后求解泵上部分流体的温度分布。

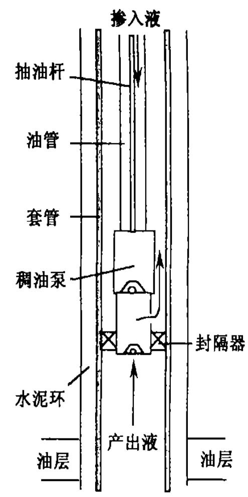

图 1　掺液稠油泵井筒示意图

2.1　泵下井筒流体温度分布模型

泵下井筒流体的温度分布模型为[1]

$$\begin{cases} \dfrac{\mathrm{d}T_f}{\mathrm{d}h} = \dfrac{T_{e0} + g_T h - T_f}{s} - \dfrac{g\sin\lambda}{g_c J C_{pm}} + \Phi, \\ h = H_w, \quad T_f = T_{e0} + g_T H_w. \end{cases} \tag{1}$$

其中

$$s = \frac{C_{pm} w}{2\pi}\left[\frac{\lambda_r + RUf(t)}{\lambda_r RU}\right].$$

$$\Phi = C_J \frac{\mathrm{d}p}{\mathrm{d}h} - \frac{v\mathrm{d}v}{g_c J C_{pm}\mathrm{d}h}.$$

式中, T_f 为井筒流体温度, ℃; h 为深度, m; T_{e0}为

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地表恒温层温度,℃; g_T 为地温梯度,℃/m; λ 为井斜角,rad; C_{pm}为流体定压比热,J/(kg·℃); H_w 为油层中部深度,m; g、g_c、J 均为常数; s 为热衰减距离,m; Φ 表示由于相变而引起的焦耳-汤姆森效应; w 为流体质量流量,kg/s; λ_r 为地层岩石导热系数,W/(m·℃); R 为管流半径,m; U 为总传热系数,W/(m^2·℃); $f(t)$ 为无因次时间函数; v 为流速,m/s; p 为压力,Pa; C_J 为焦耳-汤姆森系数。

解式(1)得到泵下井筒流体的温度分布

$$T_f = T_{e0} + g_T h + s\left(\frac{g\sin\lambda}{g_c J C_{pm}} - \Phi + g_T\sin\lambda\right) \times \left[\exp\left(\frac{H_w - h}{s}\right) - 1\right]. \qquad (2)$$

2.2　泵上井筒流体温度分布模型

油管内的掺入液仅与环空中的混合液发生热交换,因此有[2]:

$$\mathrm{d}q = -C_t \mathrm{d}T = \frac{2\pi R_{ti} U_t (T - \theta)}{w_t}\mathrm{d}h. \qquad (3)$$

式中, q 为换热量,J/kg; T 为油管掺入液温度,℃; θ 为环空混合液温度,℃; C_t 为油管掺入液比热,J/(kg·℃); R_{ti}为油管内半径,m; w_t 为掺入液质量流量,kg/s; U_t 为油管传热系数,W/(m^2·℃)。

变换式(3)得到关于油管掺入液温度的微分方程:

$$\frac{\mathrm{d}T}{\mathrm{d}h} = \frac{2\pi R_{ti} U_t (\theta - T)}{w_t}. \qquad (4)$$

油套环空中的混合液不但和油管内掺入液发生热交换,而且随着时间变化和周围地层发生热交换。与地层之间的热交换为[3]

$$\mathrm{d}q = \frac{2\pi}{w_c}\frac{\lambda_r R_{ci} U_c}{\lambda_r + R_{ci} U_c f(t)}[\theta - (T_{e0} + g_T h)]\mathrm{d}h. \qquad (5)$$

式中, w_c 为环空混合液质量流量,kg/s; U_c 为套管传热系数,W/(m^2·℃); R_{ci}为套管半径,m。

环空混合液与外界的热量交换等于其与油管掺入液和地层的热交换之和,即

$$\frac{\mathrm{d}q}{\mathrm{d}h} = \frac{2\pi R_{ti} U_t (\theta - T)}{w_t} + \frac{2\pi}{w_c}\frac{\lambda_r R_{ci} U_c}{\lambda_r + R_{ci} U_c f(t)}[\theta - (T_{e0} + g_T h)]. \qquad (6)$$

根据 Hasan 等研究结果,泵上部分井筒流体温度分布方程为[1]

$$\frac{\mathrm{d}\theta}{\mathrm{d}h} = \frac{1}{C_{pm}}\left[\frac{\mathrm{d}q}{\mathrm{d}h} - \frac{g\sin\lambda}{g_c J} - \frac{v}{g_c J}\frac{\mathrm{d}v}{\mathrm{d}h}\right] + C_J\frac{\mathrm{d}p}{\mathrm{d}h}. \qquad (7)$$

将式(6)代入式(7)得到

$$\frac{\mathrm{d}\theta}{\mathrm{d}h} = \frac{2\pi R_{ti} U_t}{C_c w_t}(\theta - T) + \frac{2\pi\lambda_r R_{ci} U_c}{C_c w_c[\lambda_r + R_{ci} U_c f(t)]} \times [\theta - (T_{e0} + g_T h)] - \frac{g\sin\lambda}{C_c g_c J} + \Phi. \qquad (8)$$

由式(4,8)建立微分方程组,得到泵上井筒液体(包括油管掺入液和环空混合液)的温度分布模型为

$$\begin{cases} \dfrac{\mathrm{d}T}{\mathrm{d}h} = \dfrac{2\pi R_{ti} U_t (\theta - T)}{w_t}, \\ \dfrac{\mathrm{d}\theta}{\mathrm{d}h} = \dfrac{2\pi R_{ti} U_t}{C_c w_t}(\theta - T) + \dfrac{2\pi\lambda_r R_{ci} U_c}{C_c w_c[\lambda_r + R_{ci} U_c f(t)]} \times \\ \qquad [\theta - (T_{e0} + g_T h)] - \dfrac{g\sin\lambda}{C_c g_c J} + \Phi. \end{cases} \qquad (9)$$

根据质量守恒和能量守恒得到如下边界条件:

$$\begin{cases} h = 0 \text{ 时}, \ T = T_0, \ \theta = \theta_0; \\ h = H_p \text{ 时}, \ T = T_p, \ \theta = \theta_p; \\ w_t + w_1 = w_c; \\ w_t C_t + w_1 C_1 = w_c C_c; \\ w_t C_t T_p + w_1 C_1 T_{1p} = w_c C_c \theta_p. \end{cases}$$

式中, w_1 为地层产出液质量流量,kg/s; C_1 为地层产出液比热,J/(kg·℃); C_c 为环空混合液比热,J/(kg·℃); H_p 为下泵深度,m; T_0 为掺入液地面温度,℃; T_p 为掺入点掺入液温度,℃; T_{1p}为掺入点地层产出液温度,℃; θ_p 为掺入点环空混合液温度,℃; θ_0 为地面环空混合液温度,℃。

3　有关参数的计算

井筒附近地层从井筒流体获得热量,同时将部分热量扩散到深部地层,使地层温度不断升高直到平衡。而井筒流体向地层的传热过程与井筒附近地层有关,因此,井筒流体温度分布与时间有关。通过无因次时间函数可以考虑生产时间对井筒温度分布的影响。无因次时间函数 $f(t)$ 的确定方法如下[2]:

$$\alpha_e = \lambda_r/(C_e\rho_e).$$

$$f(t) = -\ln\frac{R_{wb}}{2\sqrt{\alpha_e t}} - 0.29.$$

式中, α_e 为地层岩石热扩散(导温)系数,m^2/s; C_e 为地层岩石比热,J/(kg·℃); ρ_e 为地层岩石密度,kg/m^3; t 为生产时间,s; R_{wb}为井眼半径,m。

文献[1]给出了计算焦耳-汤姆森系数 Φ 的经验公式:

$$\Phi = -0.00297 + 6.93\times10^{-9}p_{wh} + 8.645\times10^{-5}w - 1.047\times10^{-6}F_{gl} + 3.229\times10^{-5}API + 0.004009\gamma_g - 0.3551g_T$$

式中, p_{wh}为井口压力,Pa; w 为流体质量流量,kg/s; F_{gl}为气液比; API 为原油 API 度; γ_g 为气相相对

密度。

4　计算方法及算例

泵上井筒液体的温度分布模型(式(9))是一个非齐次线性常微分方程组,首先求出其齐次方程组的通解,然后使用拉格朗日常数变易法得到一个特解,最后得到式(9)的通解,再由边界条件求得具体解[4]。得到的泵上井筒流体温度分布方程中含有如下几个参数:T_{1p},T_0,T_p,θ_p,θ_0。其中 T_0 已知,T_{1p}可以由式(2)求得,其余 T_p、θ_p、θ_0 未知。由式(9)的边界条件可以消去一个未知量 T_p,而 θ_p、θ_0 可以用迭代法计算得到。

算例　井深 1 500 m,用稠油泵举升,下泵深度 880 m,泵的掺入液与油层液的理论比值为 1∶1.388,掺水量 54 m^3/d,油层液量 40 m^3/d,含水 20 %,地面掺入液温度 42 ℃。计算得到生产 4 d 后的井筒温度分布见图 2,生产 50 d 后的温度分布见图 3。

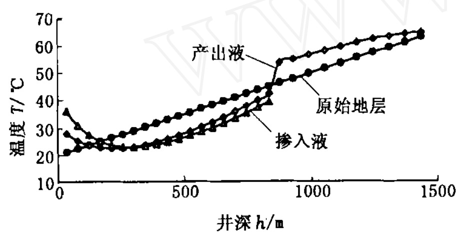

图 2　稠油泵井筒温度场分布(t = 4 d)

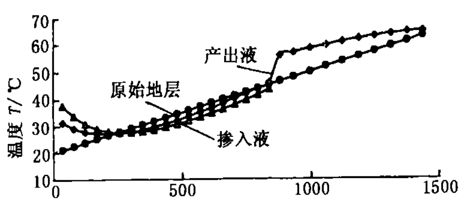

图 3　稠油泵井筒温度场分布(t = 50 d)

产出液向上流动过程中,由于向地层散热而使温度略有降低,到达稠油泵后与相对低温的地面掺入液混合,温度突然降低。由于地面掺入液与环空混合液之间仅隔一层油管,其热阻很小,所以油管掺入液温度与环空混合液温度接近。

比较图 2,3 看出,稠油泵井筒温度分布随着时间不断变化。生产初期,流体温度与地层温度相差较大,生产一段时间后,由于井筒流体与地层之间的热交换趋于平衡,井筒流体温度升高,逐渐接近于地层温度。图 4 给出了焦耳-汤姆森效应(Φ = 0.093)对套管内产出液温度的影响。由图看出,焦耳-汤姆森效应使井筒内流体温度降低。这是由于井筒内流体压力随深度减小而降低,部分溶解气逸出膨胀,使流体温度略有降低。对于油管掺液稠油泵井,焦耳-汤姆森效应对泵下井筒流体的温度影响更大些。

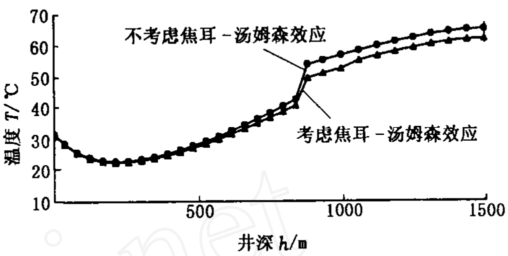

图 4　焦耳-汤姆森效应对井筒流体温度的影响

5　结　论

(1) 建立了稠油泵井筒温度分布数学模型,求解得到油管掺入、环空产出情况下的油管掺液稠油泵井筒温度分布;模型考虑了焦耳-汤姆森效应,并将时间引入到温度分布模型中,从而可以预测不同生产时间的井筒温度分布;

(2) 一定条件下,生产时间与焦耳-汤姆森效应对井筒流体温度分布有明显的影响。生产时间越长,井筒流体温度越趋近于地层温度;焦耳-汤姆森效应有降低井筒流体温度的作用,其对泵下部分井筒流体温度的影响更明显。

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parameter γ related with crack density are obtained using azimuthal NMO velocities of P-P wave, P-S1 wave and P-S2 wave in multicomponent seismic data. The numerical results indicate that the NMO velocity of S-wave can be comparatively exactly computed by using NMO velocities of P-P wave and P-S wave in HTI media with moderate strength of anisotropy, which provides a reliable basis for the inversion of Thomsen parameters using 2D multicomponent seismic data.

Key words: horizontal transverse isotropic media; double profile; normal moveout velocity; anisotropic parameters; S-wave velocity; inversion

EXPERIMENTAL STUDY ON MECHANISMS OF HYDRAULIC SAND BLASTING PERFORATION FOR IMPROVEMENT OF OIL PRODUCTION/ *LI Gen-sheng, NIU Ji-lei, LIU Ze-kai, et al. College of Petroleum Engineering in the University of Petroleum, China, Dongying* 257061/ *Shiyou Daxue Xuebao*, 2002, 26(2):31～34.

On the basis of erosion wear theory of materials and the abrasive water jet cutting process, the mechanisms of both casing cutting and formation rock cutting with hydraulic sand blasting perforation of oil wells are discussed, and the influencing parameters are investigated. The preliminary experiments of hydraulic sand blasting perforation both in laboratory and on field are conducted. The simulation experiment in laboratory shows that the casing can be easily cut with the hydraulic sand blasting perforation. The sandstone can be perforated, and a hole with 30 mm in diameter and 780 mm in depth can be made on the sandstone at jetting pressure of 23～24 MPa. The field tests show the promising potential enhancement of oil production with the technique. The improvement of oil production with hydraulic sand blasting perforation is mainly resulted from the removement of the near-wellbore pollution, looseness of the compacted zone, increase of the formation permeability, which extends the passage-way of oil flow.

Key words: hydraulic sand blasting; perforation; abrasive water jet; mechanism of enhanced oil production; experimental study

BENDING ANALYSIS ON DRILLING STRING IN WHIPSTOCK OF ULTRASHORT TURNING-RADIUS HORIZONTAL WELL / *WANG Hui-yi, LI Cong-xin, RUAN Xue-yu, et al. College of Mechanical and Electronic Engineering in the University of Petroleum, China, Dongying* 257061/ *Shiyou Daxue Xuebao*, 2002, 26(2):35～37.

The affecting factors and degrees on the bending of coiled tubing drill pipe are analyzed. Since the strain hardenability of coiled tubing is low, and the plastic deformation of drill pipe is limited, the hardenability and the change of cross-section area of drill pipe effected by plastic deformation can be neglected practically. By using the model of elastic-rigid plastic constitutive relation and plane stress model, the correlation of elastic layer in drill pipe with curvature of the drill pipe under an inner pressure is determined, and the relations of limit moment and the middle layer of strain with inner pressure and axial load of drill pipe are also suggested. According to the material of drill pipe and the track of whipstock, it is concluded that the middle layer of the bent drill pipe is less affected by the curvature, but the position of middle layer is quitely affected by the inner pressure and axial load. The bent drill pipe shows a press-bending feature on the cross-section and a stretch-bending feature along the axial direction under the action of inner pressure and the axial resistance during drilling process. This result can provide a theoretical foundation for controlling the deformation of cross-secton of drill pipe and for the design of the track of whipstock.

Key words: ultrashort turning-radius horizontal well; whipstock; elastic layer; elastic-plastic bending; coiled tubing; limit moment

CALCULATION OF FLUID TEMPERATURE DISTRIBUTION IN WELLBORE WITH HEAVY OIL PUMP/ *DONG Chang-yin, ZHANG Qi, LI Zhi-fen, et al. College of Petroleum Engineering in the University of Petroleum, China, Dongying* 257061/ *Shiyou Daxue Xuebao*, 2002, 26(2):38～40.

According to the theory of heat exchange and energy balance, an array of ordinary differential equation for calculating the fluid temperature distribution in the wellbore with heavy oil pump is established in consideration of the heat exchange between the produced fluid in the annular space and the the injected fluid from pipeline, as well as the Joule-Tomphson effect caused by the phase change of liquid. The relationship of temperature distribution to production time is discussed. On the basis of the mathematical model, a computer program is designed. The calculation result shows that the program can be used to calculate conveniently the temperature distribution of mixed or produced liquid in any depth of wellbore at any time. The analysis on an application case demonstrates that the model and the calculation result are reasonable. The producing time and Joule-Tomphson effect have the important effects on the fluid temperature distribuiotn in wellbore.

Key words: heavy oil pump; temperature distribution; Joule-Tomphson effect; time function; mathematical model

APPLICATION OF ANALYTICAL INFLOW PERFORMANCE RELATIONSHIP TO PRODUCTION CAPACITY EVALUATION/ *SHI Yun-qing, ZHENG Xiang-ke and HE Shun-li. Department of Reservoir Development in Zhongyuan Oilfield, Puyang* 457001 / *Shiyou Daxue Xuebao*, 2002, 26(2): 41～43.

The method for solving dynamic relational expression of inflow performance relationship (IPR) for gas phase in oil well is presented from the Wiggins works. In practice, the gas production dynamics of oil well is often ignored though it is a base of production management for gas driven wells. The inflow funtion distribution of original production of Chang-6 reservoir in Jingan oilfield of Changqing area is obtained. Some relational expressions of inflow dynamics of oil phase, gas phase and water phase are solved. The result of calculation is compared with that of experienced relationship commonly used and the field data. The practicability and adaptability of analytical IPR are proved.

Key words: analytical inflow performance relationship; gas phase; inflow performance; low-permiability reservoir; production capacity evaluation

IDENTIFICATING METHOD FOR THE PRINCIPAL PERMEABILITY AND THE DIRECTION OF FRACTURE IN THE FRACTURED RESERVOIRS/ *LI Hong, PENG Su-ping and ZHANG De-zhi. China University of Mining Technology, Beijing* 100083/ *Shiyou Daxue Xuebao*, 2002, 26(2): 44～46.

On the basis of dual porosity physical model, a mathematical model for interference test in fractured reservoir is developed. The Laplace space solution of this model can be derived by Laplace transforms. A numerical inversion method presented by Stehfest is used to work out the approximate solution of pressure distribution in reservoir. On account of the trait of searching principles of adaptive global optimization probability of inheritance algorithm, the automatic fitting technique is utilized to identify the principal permeability and the direction of fractures in fractured reservoirs. This paper presents the calculation results of the pressures observed from several wells in Shengli oilfield. This method can be used in the active wells without pressure data. The validity of this method is verified by the observed data with the interference test method. The interpretated results indicate that this interpretation mehtod presented in this paper is creditable, and the interpretated result is agreeable with the state of oilfield.

Key words: fractured reservoir; interference test; principal permeability; fracturing direction; identification; inheritance algorithm

THE MECHANISM OF PROFILE MODIFICATION OF AMPHOTERIC COPOLYMER MODIFICATION AGENT/ *LI Ai-fen, CHEN Yue-ming, KAN Chun-ling, et al. College of Petroleum Engineering in the University of Petroleum, China, Dongying* 257061/ *Shiyou Daxue Xuebao*, 2002, 26(2): 47～49.

The amphoteric copolymer profile modification agent is a novel one. It has polycation, polyanion and nonion in its molecular chain. The component, the action mechanism and the basic formulation of the profile modification agent are studied. More than 40 formulations of the agent are developed. Among them, the amphoteric copoly-