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CALCULATION ALGORITHM DEFINING THE COEFFICIENT OF HYDRAULIC RESISTANCE ON DIFFERENT AREAS OF PUMP-COMPRESSOR PIPES IN GAS LIFT PROCESS BY LINES METHOD

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Abstract

In this paper the process of gas-lift in the oil production is considered. In this process the motions of gas and gas-liquid mixture (GLM) are described by the system of partial differential equations of hyperbolic type. Applying lines method the system of partial differential equations of hyperbolic type is reduced to the system of ordinary differential equations with respect to the volumes of gas, GLM and their pressures. Applying least-squares method, the coefficient of hydraulic resistance (CHR) is obtained on different areas of pump-compressor pipes. On the concrete example the adequacy of the mathematical model is shown.

Keywords:
Gas lift;
Gas-liquid mixture;
Identification;
Algebraic equations;
Coefficient of hydraulic resistance;
Least-squares method.

Introduction

As it is known [1-4], the gas-lift method for oil production [5-8] is used when the fountain method impossible due to the lower reservoir pressure. Defining the CHR [9-13] during the motion of the GLM in the lift takes an important place [1, 2, 12-16]. Such problems were considered in [17-19], in which the CHR was defined on all length of pump-compressor pipes (PCP). However, such approach doesn't allow defining the CHR on the certain required areas of PCP. Therefore, by means of lines method the initial problem is reduced to the system of ordinary differential equations with respect to the volume of gas, GLM and their pressures. Using statistical data for the fixed well and least squares method the corresponding quadratic functional is formed. Minimization of this functional with respect to the CHR gives the required result. The results are illustrated on the concrete practical example.

Problem statement

As it is known [20, 21], the motions of gas and GLM in the tubes are described by the following system of partial differential equations of hyperbolic type

$$\begin{cases} \dfrac{\partial P_i}{\partial t} = -\dfrac{c_i^2}{F_i}\dfrac{\partial Q_i}{\partial x} \\ \dfrac{\partial Q_i}{\partial t} = -F_i\dfrac{\partial P_i}{\partial x} - 2a_iQ_i \end{cases}, i = 1, 2, \qquad (1)$$

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where $P_i=P_i(x,t)$ - pressures of gas and gas-liquid mixture, respectively;

Q_i – volumes of gas and GLM, respectively, i=1,2.

$2a_i = \dfrac{g}{\omega_i} + \dfrac{\lambda_i \omega_i}{2D_i}$; the parameters c_i, a_i, ω_i, g_i, λ_i, D_i, F_i(i=1,2) have specific practical meanings and are determined as in [22, 23]. Appling lines method [24] and denoting $l_p = \dfrac{1}{n}$, $p = \overline{1,n}$, we obtain from (1)

$$\begin{cases} \dfrac{dP_k}{dt} = -\dfrac{c_i^2}{F_i l}(Q_k - Q_{k-1}) \\ \dfrac{dQ_k}{dt} = -\dfrac{F_i}{l}(P_k - P_{k-1}) - 2a_iQ_k \end{cases}, \quad i=1,2, \quad k = \overline{0, 2n} \qquad (2)$$

$$F_i = \begin{cases} F_1, & 0 < k \le n \\ F_2, & n < k \le 2n \end{cases}, \qquad c_i = \begin{cases} c_1, & 0 < k \le n \\ c_2, & n < k \le 2n \end{cases},$$

$$a_i = \begin{cases} a_1, & 0 < k \le n \\ a_2, & n < k \le 2n, \end{cases}$$

Note that for k=n+1 equation (2) has the following form [18]

$$\begin{cases} \dfrac{dP_{n+1}}{dt} = -\dfrac{c_2^2}{F_2 l}Q_{n+1} + \dfrac{c_2^2}{F_2 l}Q_n + \dfrac{c_2^2}{F_2 l}Q_{pl}, \\ \dfrac{dQ_{n+1}}{dt} = -\dfrac{F_2}{l}P_{n+1} + \dfrac{F_2}{l}P_n - 2a_2Q_{n+1} + \dfrac{F_2}{l}P_{pl}, \end{cases}$$

where Q_{pl}, P_{pl} are volume flow and pressure of the reservoir at the bottom of the well.

After some transformations system (2) can be reduced to the form [25]

$$\begin{cases} \dot{x}_1(t) = A_1(a_2(\lambda_1))x_1(t) + B_1u_0 + V \\ \dot{x}_2(t) = A_2(a_2(\lambda_2))x_2(t) + B_2u_1 \\ \dots \\ \dot{x}_n(t) = A_n(a_2(\lambda_n))x_n(t) + B_nu_{n-1} \end{cases}, \quad (3)$$

with initial condition $x_m(0) = \begin{bmatrix} P_m(0) \\ Q_m(0) \end{bmatrix}$, $m = \overline{1,n}$, where

$$\dot{x}_m(t) = \begin{bmatrix} \dot{P}_m(t) \\ \dot{Q}_m(t) \end{bmatrix}, \quad x_m(t) = \begin{bmatrix} P_m(t) \\ Q_m(t) \end{bmatrix},$$

$$A_m = \begin{bmatrix} 0 & -\frac{c_2^2}{F_2 l_m} \\ -\frac{F_2}{l_m} & -2a_2(\lambda_m) \end{bmatrix}, \quad B_m = \begin{bmatrix} 0 & \frac{c_2^2}{F_2 l_m} \\ \frac{F_2}{l_m} & 0 \end{bmatrix}, \quad u_c = \begin{bmatrix} P_c \\ Q_c \end{bmatrix},$$

$$V = \begin{bmatrix} 0 & \frac{c_2^2}{F_2 l_1} \\ -\frac{F_2}{l_1} & 0 \end{bmatrix} \cdot \begin{bmatrix} P_{pl} \\ Q_{pl} \end{bmatrix}, \; m = \overline{1,n}, \;\; i = \overline{1,2}, \; c = \overline{0, n-1}.$$

Defining the CHR [1, 26] in practice is a laborious problem. In [9-11, 27, 28] the CHR was defined on all length of PCP. However, in practice usually the CHR is different on different areas of PCP on all over depth.

Note that in PCP of gas-lift wells the CHR λ_m, $m = \overline{1,n}$ changes its value on the interval $0 \le \lambda_m \le 1$ [9]. Suppose that the CHR - λ_m $(m = \overline{1,n})$, (λ_1 corresponds to the beginning of the bottom of the well, λ_n corresponds to the end of PCP, where $\lambda_1 > \lambda_1 > \ldots > \lambda_n$), $Q_0^{s,st}$ (the volume of injected gas at the wellhead of the annular space), $Q_0^{s,st}$ (GLM at the end of the lift) from the statistical data on different areas of PCP are known, $s = \overline{1,k}$ (s – number of statistical data) [1].

Thus, the problem of defining such λ_m $(m = \overline{1,n})$ is reduced to the minimization of the following quadratic functional

$$I(\lambda_1, \lambda_2, \ldots, \lambda_n) = \sum_{s=1}^{k} [Q_n^s(\lambda_1, \lambda_2, \ldots, \lambda_n, T) - Q_n^{s,st}]^2 \to \min. \quad (4)$$

Method of solution

For solving the system (3) with initial condition

$$x_m(0) = \begin{bmatrix} P_m(0) \\ Q_m(0) \end{bmatrix}, \; m = \overline{1,n}$$

in intervals $[0,l_1]$, $[l_1,l_2]$,..., $[l_{n-1},l_n]$,($[0+ l_1 +\ldots+ l_n = l$) we obtain the general solution of system (3)

$$\begin{aligned} x_n(t) = {} & e^{A_n t}x_n(0) + \sum_{m=1}^{n-1}(-1)^m \left(\prod_{j=n}^{m+1} A_j^{-1}B_j(E - e^{A_j t}) \right) e^{A_i t}x_i(0) + \\ & +(-1)^n \left(\prod_{m=1}^{n} A_m^{-1}B_m(E - e^{A_m t}) \right) u_0 + \\ & +(-1)^n \left(\prod_{m=2}^{n} A_m^{-1}B_m(E - e^{A_m t}))(A_1^{-1}(E - e^{A_1 t}) \right) V \end{aligned} \quad (5)$$

where E - is a unit matrix.

From (5) it follows $Q_n(\lambda_1, \lambda_2, \ldots, \lambda_n, T)$ has the next form

$$Q_n(\lambda_1, \lambda_2, \ldots, \lambda_n, T) = [0 \;\; 1]'x_n(T = Jx_n(T) \quad (6)$$

where $J = [0 \;\; 1]'$

Inserting (5) and (6) in (4), we get

$$\begin{aligned} I = {} & \sum_{s=1}^{k}[Q_n^s(\lambda_1, \lambda_2, \ldots, \lambda_n, T) - Q_n^{s,st}]^2 = \sum_{s=1}^{k}[Jx_n^s(T) - Q_n^{s,st}]^2 = \\ = {} & \sum_{s=1}^{k}[Je^{A_n T}x_n^s(0) + J\sum_{m=1}^{n-1}(-1)^m \left(\prod_{j=n}^{m+1} A_j^{-1}B_j(E - e^{A_j T}) \right) e^{A_i T}x_i^s(0) + \\ & +J(-1)^n \left(\prod_{m=1}^{n} A_m^{-1}B_m(E - e^{A_m T}) \right) u_0 + \\ & +J(-1)^n \left(\prod_{m=2}^{n} A_m^{-1}B_m(E - e^{A_m T}) \right) (A_1^{-1}(E - e^{A_1 T}))V - Q_n^{s,st}]^2 \end{aligned} \quad (7)$$

To solve the optimization problem (3)-(4) we find the gradient of functional $I(\lambda_1, \lambda_2, \ldots, \lambda_n)$ and equate it to zero. The gradient vector calculating for $I(\lambda_1, \lambda_2, \ldots, \lambda_n)$ is practically impossible. Therefore by means of the following formulas we calculate the gradient vector $\frac{\partial I}{\partial \lambda_i}$, $i = \overline{1,n}$ as [29].

$$\begin{cases} \dfrac{\partial I(\lambda_1, \lambda_2, \ldots, \lambda_n)}{\partial \lambda_1} = \dfrac{I(\lambda_1 + h_1, \lambda_2, \ldots, \lambda_n) - I(\lambda_1 - h_1, \lambda_2, \ldots, \lambda_n)}{2h_1}, \\ \dfrac{\partial I(\lambda_1, \lambda_2, \ldots, \lambda_n)}{\partial \lambda_2} = \dfrac{I(\lambda_1, \lambda_2 + h_2, \ldots, \lambda_n) - I(\lambda_1, \lambda_2 - h_2, \ldots, \lambda_n)}{2h_2}, \\ \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \\ \dfrac{\partial I(\lambda_1, \lambda_2, \ldots, \lambda_n)}{\partial \lambda_n} = \dfrac{I(\lambda_1, \lambda_2, \ldots, \lambda_n + h_n) - I(\lambda_1, \lambda_2, \ldots, \lambda_n - h_n)}{2h_n}, \end{cases} \quad (8)$$

where $h_i, i = \overline{1,n}$ are small parameters.

Thus, we formulate the following algorithm for finding CHR λ_i (i = 1, n):

Algorithm

1. The initial data and parameters are introduced from (3);
2. The statistical data (observations) $Q_0^{s,st}$ (initial volume of gas), $Q_n^{s,st}$ (debit at the output of the well) from the practice for the same well;
3. $Q_n(\lambda_1, \lambda_2, \ldots, \lambda_n, T)$ is defined from (6);
4. The functional (7) is formulated;
5. By means of (8), the solutions of the equations

$$\frac{\partial I(\lambda_1, \lambda_2, \ldots, \lambda_n)}{\partial \lambda_1} = 0, \quad \frac{\partial I(\lambda_1, \lambda_2, \ldots, \lambda_n)}{\partial \lambda_2} = 0, \ldots, \quad \frac{\partial I(\lambda_1, \lambda_2, \ldots, \lambda_n)}{\partial \lambda_n} = 0$$

are founded;

6. For sufficiently small number ε the conditions

$$\left|\frac{\partial I(\lambda_1,\lambda_2,...,\lambda_n)}{\partial\lambda_1}\right|<\varepsilon,...,\left|\frac{\partial I(\lambda_1,\lambda_2,...,\lambda_n)}{\partial\lambda_n}\right|<\varepsilon$$

are checked. If they are satisfied, then the calculating process ends, otherwise decreasing $h_i, i=\overline{1,n}$ we go to the step 2.

The case *n*=2

Let's consider the simple case, taking n=2, i.e. the length of the pump-compressor pipes is divided into two different parts $[0,l_1]$, $[l_1,l_2]$ $(l_1+l_2=l)$. Assume that from the statistical data $Q_0^{s,st}$ (at the wellhead of the annular space), $Q_2^{s,st}$ (at the end of the annular space) are known, $s=\overline{1,k}$ (k –the number of statistical data).

Then the quadratic functional has the next form

$$I(\lambda_1,\lambda_2)=\sum_{s=1}^{k}[Q_2^s(\lambda_1,\lambda_2,.T)-Q_2^{s,st}]^2.$$

$Q_2(\lambda_1,\lambda_2,T)$ here is defined similarly to (6). Then we get

$$I(\lambda_1,\lambda_2)=\sum_{s=1}^{k}[Q_2^s(\lambda_1,\lambda_2,.T)-Q_2^{s,st}]^2=\sum_{s=1}^{k}[Jx_2^s(T)-Q_2^{s,st}]^2=$$

$$=\sum_{s=1}^{k}[Je^{A_2T}x_2^s(0)-JA_2^{-1}\left(E-e^{A_2T}\right)B_2e^{A_1T}x_1^s(0)+ \tag{9}$$

$$+A_2^{-1}(E-e^{A_2T})B_2A_1^{-1}\left(E-e^{A_1T}\right)\left(B_1u_0+V\right)-Q_2^{s,st}]^2.$$

For defining CHR in pump-compressor pipes the functional (9) is minimized with respect to λ_1 and λ_2. Then the gradient of the functional with respect to λ_1 and λ_2 is definite and $\partial I/\partial\lambda_1$ and $\partial I/\partial\lambda_2$ are equated to zero

$$\frac{\partial I}{\partial\lambda_1}=2\sum_{s=1}^{k}([Je^{A_2T}x_2^s(0)-JA_2^{-1}\left(E-e^{A_2T}\right)B_2e^{A_1T}x_1^s(0)+$$

$$+A_2^{-1}\left(E-e^{A_2T}\right)B_2A_1^{-1}\left(E-e^{A_2T}\right)\left(B_1u_0+V\right)-Q_2^{s,st}]\times$$

$$\times(-JA_2^{-1}\left(E-e^{A_2T}\right)B_2A_4Te^{A_1T}x_1^s(0)+ \tag{10}$$

$$+A_2^{-1}\left(E-e^{A_2T}\right)B_2\left(-A_1^{-1}A_4A_1^{-1}\right)\left(E-e^{A_2T}\right)\left(B_1u_0+V\right)+$$

$$+A_2^{-1}\left(E-e^{A_2T}\right)B_2A_1^{-1}(E-A_4T)\left(B_1u_0+V\right)))=0$$

where $A_1=A_3+\lambda_1A_4$

$$A_3=\begin{bmatrix}0 & -\dfrac{c_2^2}{F_2l_1}\\ -\dfrac{F_2}{l_1} & -\dfrac{g_2}{\omega_2}\end{bmatrix},\quad A_4=\begin{bmatrix}0 & 0\\ 0 & -\dfrac{\omega_2}{2D_2}\end{bmatrix},$$

$$\frac{\partial I}{\partial\lambda_2}=2\sum_{s=1}^{k}([Je^{A_2T}x_2^s(0)-JA_2^{-1}\left(E-e^{A_2T}\right)B_2e^{A_1T}x_1^s(0)+$$

$$+A_2^{-1}\left(E-e^{A_2T}\right)B_2A_1^{-1}\left(E-e^{A_1T}\right)(B_1u_0+V)-Q_2^{s,st}]\times$$

$$\times(JA_4Tx_2^s(0)--J\left(-A_2^{-1}A_4A_2^{-1}\right)\left(E-e^{A_2T}\right)B_2e^{A_1T}x_1^s(0)-$$

$$-JA_2^{-1}(E-A_4T)B_2e^{A_1T}x_1^s(0)+ \tag{11}$$

$$+\left(-A_2^{-1}A_4A_2^{-1}\right)\left(E-e^{A_2T}\right)B_2A_1^{-1}\left(E-e^{A_1T}\right)(B_1u_0+V)+$$

$$+A_2^{-1}(E-A_4T)B_2A_1^{-1}\left(E-e^{A_1T}\right)(B_1u_0+V)))=0$$

where $A_2=A_5+\lambda_2A_4$

$$A_5=\begin{bmatrix}0 & -\dfrac{c_2^2}{F_2l_2}\\ -\dfrac{F_2}{l_2} & -\dfrac{g_2}{\omega_2}\end{bmatrix}.$$

Thus,solving the algebraic equations (10) and (11) with respect to λ_1 and λ_2 on two different areas of pump-compressor pipes the CHR is defined.

Let's consider the realization of the proposed algorithm on the example [9]. After applying the proposed algorithm we obtain that λ_1=0.2303689622 on the interval $[0,l_1]$, λ_2=0.1151447401 on the interval $[l_1,l_2]$, where λ_1 differs from $\tilde{\lambda}_1=0.23$ ($\tilde{\lambda}_1$ is the value of CHR on the interval $[0,l_1]$ from practice) to the order 10^{-4}, λ_2 differs from $\tilde{\lambda}_2=0.1$ ($\tilde{\lambda}_2$ is the value of CHR on the interval $[l_1,l_2]$ from practice) to the order 10^{-2}.

Conclusion

For defining CHR analytical formulas (10) and (11) are obtained, where the length of PCP is divided into two different parts and the length of PCP is divided into more than two parts. Also for defining CHR the formula (8) is used.

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Вычислительный алгоритм, определяющий коэффициент гидравлического сопротивления на различных участках насосно-компрессорных труб в газлифтом процессе линейным методом

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Реферат

В работе рассматривается процесс газлифта при добыче нефти, где движения газа и газожидкостной смеси (ГЖС) в соответствующих трубах описывается системой дифференциальных уравнений с частными производными гиперболического типа. С помощью метода прямых система дифференциальных уравнений в частных производных гиперболического типа сводится к системе обыкновенных дифференциальных уравнений по объемам газа, ГЖС и их давлениям. Применяя метод наименьших квадратов определен коэффициент гидравлического сопротивления (КГС) на каждом заданном участке подъемника, используя статистические данные (объем подаваемого газа на устье кольцевого пространства и объем ГЖС в конце подъемника). Приводится пример, который показывает адекватность математической модели.

Ключевые слова: газлифт; газожидкостная смесь; идентификация; алгебраические уравнения; коэффициент гидравлического сопротивления; метод наименьших квадратов.

Qaz-lift prosesində düz xətlər üsulunda istifadə edərək nasos-kompressor borunun müxtəlif hissələrində hidravlik müqavimət əmsalının təyini üçün hesablama alqoritmi

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Xülasə

İşdə neftin hasilatı zamanı qaz-lift prosesi nəzərdən keçirilir. Bu zaman müvafiq borulardakı qaz və qaz-maye qarışığının hərəkəti hiperbolik tipli xüsusi törəməli diferensial tənliklər sistemi vasitəsilə təsvir olunur. Düz xətlər üsulundan istifadə edərək hiperbolik tipli xüsusi törəməli diferensial tənliklər sistemi qaz və qaz-maye qarışığının həcmi və onların təzyiqlərinə nəzərən adi diferensial tənliklər sisteminə gətirilir. Ən kiçik kvadratlar üsulunu tətbiq etməklə və statistik məlumatlardan istifadə edərək borunun hər bir hissəsində hidravlik müqavimət tapılır (halqavari borunun başlanğıcında verilən qazın həcmi və qaldırıcının

Açar sözlər: qazlift; qaz-maye qarışığı; identifikasiya; cəbr tənlikləri; hidravlik müqavimət əmsalı; ən kiçik kvadratlar üsulu.