IDENTIFICATION OF THE HEAT TRANSFER COEFFICIENT IN PIPELINE TRANSPORT OF HIGH-VISCOSITY READILY CONGEALING OILS

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UDC 622.692.4:536.24

A simple technique is developed for determining the heat transfer coefficient on the basis of information available about the state of transported oil in industrial oil pipelines.

The most complicated technological problem in pipeline transport is the conveyance of high-viscosity, readily congealing oils. This is associated with their physicochemical characteristics: (a) a high content of hard block paraffins, asphaltenes, and resins; (b) a high congealing temperature; (c) a strong dependence of their rheological properties on temperature. At the present time many techniques for transporting such oils have been developed. The most popular of these is "hot" transfer over pipelines. In this technique, the transported oil is heated at the main heating station and then is pumped into the pipeline. As the oil moves, it cools off, and therefore at intervals of 25-100 km intermediate heating stations are located along the pipeline.

The state of the transported oil in the pipeline is determined by the temperature $T(x, t)$, velocity $v(x, t)$ and pressure $p(x, t)$. Below, the calculations of the operational thermal regimes of oil pipelines are given.

The oil temperature in the pipeline is formed under the influence of the process of heat transfer between the moving oil and the ambient medium. The intensity of the process depends on the value of the heat transfer coefficient k. This makes it possible to assume that the accuracy of thermal calculations is predominantly determined by the accuracy of this parameter. The distribution of the oil temperature for various k is shown in Fig. 1.

The determination of the heat transfer coefficient in oil pipelines has been the concern of a large number of publications [1-4]. The basic relation for the calculation of k is [5]

$$\frac{1}{kD} = \frac{1}{2r\alpha_1} + \frac{1}{D\alpha_2} + \frac{1}{2\lambda_p} \ln \frac{r_{in}}{r} + \frac{1}{2\lambda_i} \ln \frac{D}{d_n}, \tag{1}$$

where D is the outer diameter of an insulated pipeline; r is the radius of the clear area of a paraffin-clogged pipeline; r_{in} is the inner radius of the pipe; d_{in} is the inner diameter of insulation; λ_p, λ_i are the thermal conductivity coefficients of paraffin and insulation; α_1 and α_2 are the internal and external coefficients of heat transfer.

To determine α_1 for a turbulent mode of flow, the following dimensionless equation is used [6]

$$\frac{2\alpha_1 r}{\lambda_o} = \mathrm{Nu}_o, \tag{2}$$

$$\mathrm{Nu}_o = 0.021\, \mathrm{Re}_o^{0.8}\, \mathrm{Pr}_o^{0.43} \left(\frac{\mathrm{Pr}_o}{\mathrm{Pr}_w} \right)^{0.25} \varepsilon_l. \tag{3}$$

The subscripts o and w denote that the physical properties are selected for the mean temperatures of oil and pipe wall, respectively; ε_l is a coefficient taking into account the change in the mean heat transfer coefficient along the pipe length. Since the length of the pipeline is much larger than its diameter,

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Kazakh State University. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 65, No. 6, pp. 657-662, December, 1993.

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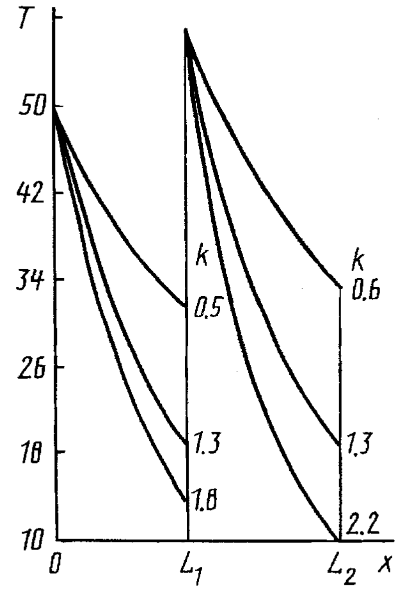

Fig. 1. Distribution of oil temperature $T(x)$ along two segments of a pipeline for various values of the heat transfer coefficient.

$$\varepsilon_l = 1\,.$$

The external coefficient of heat transfer from the pipe wall to the environment is defined by the expression [7, 8]

$$\alpha_2 = \frac{4\lambda_{gr}}{d_i \ln \left[\left(16 \frac{H^2}{d_i^2} + 1 \right) + \frac{32 H \lambda_{gr}}{\alpha_{B0} \left(16 \frac{H^2}{d_i^2} + 1 \right)} \right]}, \tag{4}$$

where

$$\alpha_{B0} = \alpha_{Bc} + \alpha_{Br}\,; \quad \alpha_{Bc} = 11.6 + 7.0 \sqrt{w_w}\,;$$

$$\alpha_{Br} = \frac{\varepsilon_{re} C_s}{T_{gr.s} - T_a} \left[\left(\frac{T_{gr.s} + A}{100} \right)^4 - \left(\frac{T_a + A}{100} \right)^4 \right];$$

α_{B0} is the coefficient of heat transfer from the ground surface to the atmosphere; α_{Bc} is the coefficient of convective heat transfer; α_{Br} is the coefficient of radiative heat transfer; H is the pipe axis depth; λ_{gr} is the thermal conductivity of the ground; w_w is the speed of the wind; ε_{re} is the reduced emissivity of the ground surface; C_s is the Stefan-Boltzmann constant; $T_{gr.s}$ and T_a are the temperature of the ground surface and the air, respectively.

The main drawback of relation (1) is the necessity for a large amount of initial information, a portion of which is difficult to determine, e.g., λ_{gr}, $T_{gr.s}$, etc.

In practice, recommendations have been developed to simplify and increase the accuracy of calculations; for example, when

$$\frac{H}{d_i} \geq 3$$

formula (4) is simplified and reduced to the form [9]

$$\alpha_2 = \frac{2\lambda_{gr}}{d_i \ln \frac{4H}{d_i}}. \tag{5}$$

To increase the accuracy of calculating k, the oil pipeline route is divided into portions with approximately uniform properties of the ground and atmospheric conditions, and for each of these the specific value of k is determined.

The accuracy of the values of k can be raised in two ways:

1) by increasing the accuracy of the initial information for relations (1)-(4). However, this is impossible to fulfill for main pipelines;

2) for each industrial oil pipeline documents are kept concerning the state of the oil transported. In them, in certain time intervals information about the oil temperature is recorded; this is called operational information (OI). On the basis of OI one can calculate the parameter k and use it in subsequent calculations. In other words, one can adapt the mathematical model that describes the flow of oil along a pipeline to the actual technological conditions by parametrically identifying the value of k.

The pipeline, as an object of identification, connects the known input parameters $x_1, ..., x_i$ and the unknown input parameters $z_1, ..., z_k$ with the known output parameters $y_1, ..., y_m$ [10]. In our case the structure of the model for the pipeline is known. It is a mathematical description of the flow of oil along the pipeline [11]. The parameter k, involved in this model, is to be identified on the basis of the available OI.

Let us consider the operation of one segment of the pipeline of length L for the time $[t_0, t_1]$. In this period, in equal time intervals t we shall record the oil temperature $T_{exit}(t)$ at the beginning and $T_{end}(t)$ at the end of the segment and the velocity $v_*(t)$. The number of recordings is determined by the expression

$$n_1 = \frac{t_1 - t_0}{\Delta t}, \quad t = t_0 + n\Delta t, \quad n = 1, 2, \ldots, n_1.$$

Knowing $T_{exit}(t)$, $T_{end}(t)$, $v_*(t)$, and $[t_0, t_1]$, it is necessary to determine the values of the heat transfer coefficient.

The direct statement of the problem for one segment of the pipeline is a system of differential equations with boundary and initial conditions [11]

$$\left\{ \begin{aligned} & \frac{\partial T}{\partial t} + v\frac{\partial T}{\partial x} = \frac{1}{\rho c}\left\{\frac{\sigma \tau v - q}{R} + \frac{1}{F}\sum_{i=1}^{N_s} \eta(t_{si})\, G_i \left[\cdot \tilde{c}_i (\tilde{T}_i + A) - \right.\right. \\ & \left.\left. - c(T + A) + \frac{(v_i \cos\alpha_i - v)^2}{2}\right] \delta(x - x_i)\right\}, \\ & \frac{\partial v}{\partial x} = \frac{1}{\rho F}\sum_{i=1}^{N_s} \eta(t_{si})\, G_i\, \delta(x - x_i), \end{aligned} \right. \tag{6}$$

$$\left\{ \begin{aligned} & T(0, t) = T_{exit}(t), \quad t_0 \le t \le t_1, \quad x = 0; \\ & T(L, t) = T_{end}(t), \quad t_0 \le t \le t_1, \quad x = L; \\ & v(0, t) = v_*(t), \quad t_0 \le t \le t_1, \quad x = 0; \\ & T(x, 0) = \psi(x), \quad t = 0, \quad 0 \le x \le L. \end{aligned} \right. \tag{7}$$

From the time $[t_0, t_1]$ we shall eliminate the lag time, which is defined as the time needed for a fixed volume of oil ΔV to pass the segment of length L with the velocity $v_*(t)$:

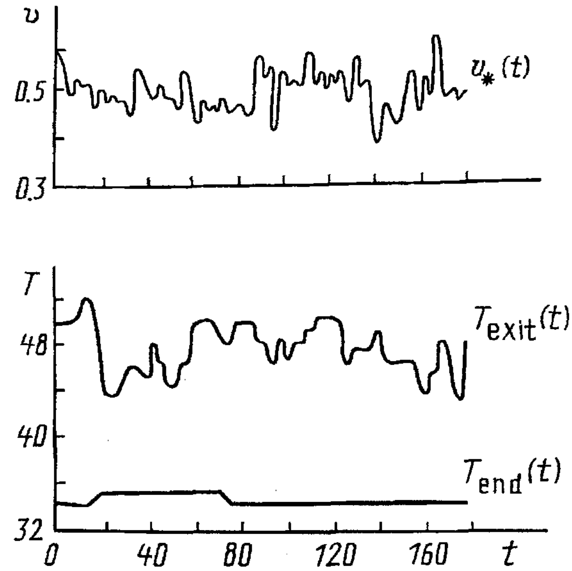

Fig. 2. An example of operative information for solving the problem of parametric identification by *k*. *t*, h.

$$t_* = n_* \Delta t, \tag{8}$$

where n_* is determined from the inequality

$$\Delta t \sum_{n=1}^{n_*} v_* (n\Delta t) \geq L. \tag{8a}$$

The value of *k* is calculated by solving a series of direct problems with subsequent approximation of the result by an *N*-degree polynomial (usually $N \leq 3$):

$$k = k(T(L, t)).$$

Let the values of the heat transfer coefficient *k* belong to a certain domain *K*. Let us select from it the sequence

$$k_1, k_2, \ldots, k_m, \tag{9}$$

and, using Eq. (6), construct the relation

$$T = T(L, k) \tag{10}$$

for a point at the end of the segment $x = L$ (because in the OI the temperature at the end of the segment is recorded). The calculated temperature at the point $x = L$ will be denoted by $T_{\text{end }c}$.

For k_i, $i = 1, 2, \ldots, m$, having solved the direct problem, we will find $T^i_{\text{end }c}$ and determine the mean value $\tilde{T}^i_{\text{end }c}$, having eliminated the lag time t_*:

$$\begin{cases} \tilde{T}^i_{\text{end }c} = \dfrac{\sum\limits_{n=n_*}^{n_1} T^{in}_{\text{end }c}}{n_1 - n_* + 1}, \\ \\ T^{in}_{\text{end }c} = T^i_{\text{end }c}(n\Delta t), \quad i = 1, 2, \ldots, m. \end{cases} \tag{11}$$

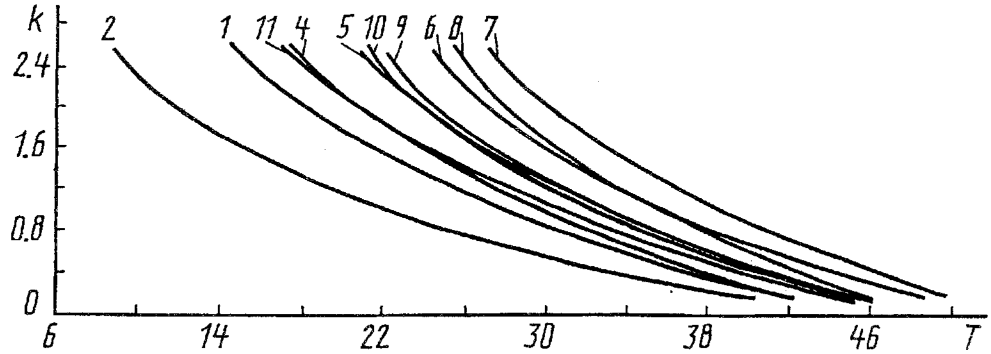

Fig. 3. The relationship $k = k(T)$ for one segment of an oil pipeline. Figures at the curves denote the months of the year.

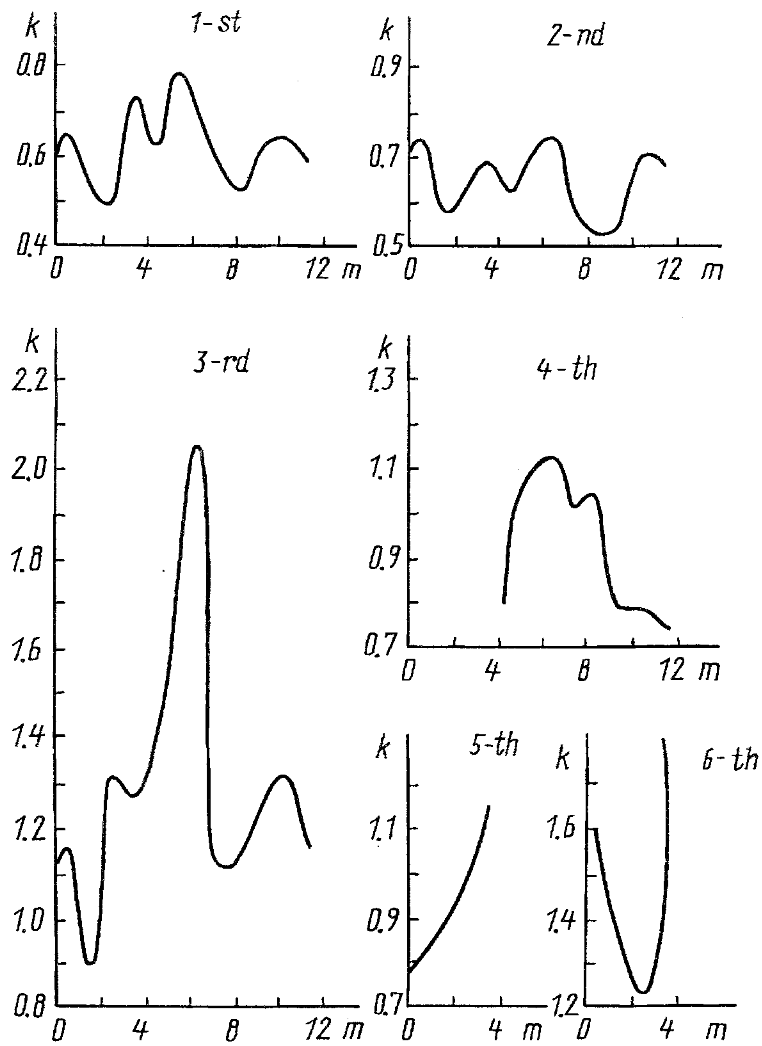

Fig. 4. Dependence of the heat transfer coefficient k on the time of the year for different segments of an oil pipeline.

As a result, we will obtain the sequence of pairs of points

$$(\tilde{T}^1_{\text{end}\,c},\ k_1),\ \ (\tilde{T}^2_{\text{end}\,c},\ k_2),\ \ldots,\ (\tilde{T}^m_{\text{end}\,c},\ k_m)\,. \tag{12}$$

Knowing this sequence, we will find the relation

$$k = k(\widetilde{T}_{\text{end } c}), \tag{13}$$

We will represent it in the form of the polynomial

$$k = \sum_{l=1}^{N} a_l T^{N-1}. \tag{14}$$

The coefficients a_l, $l = 1, 2, \ldots, N$, will be determined by the least-squares method. The degree of the polynomial N depends on the assigned accuracy of the solution $\varepsilon > 0$.

Having determined the degree of the polynomial N and the coefficients a_l, $l = 1, 2, \ldots, N$, we shall calculate from Eq. (14) the value of k corresponding to the mean experimental temperature (7):

$$\widetilde{T}_{\text{end}} = \frac{\sum_{n=n_*}^{n_1} T_{\text{end}}(n\Delta t)}{n_1 - n_* + 1}. \tag{15}$$

It is this value of k (effective) that will identify the thermal process described by the mathematical model (6), (7) with the actual technological process.

The developed procedure for determining the heat transfer coefficient k was used for calculating the thermal regimes of the operation of the Uzen'-Gur'ev main underground oil pipeline.

In Fig. 2 an example of OI on the basis of which the adaptation was performed is presented. The form of relations (11) is given in Fig. 3. The matrix A, which determines the coefficients a_l, $l = 1, 2, 3$, for different months of the year $m = 1, 2, \ldots, 12$ for one segment of the oil pipeline, has the form

$$A = \begin{Bmatrix} 4.146 & -0.148 & 0.001 \\ 3.107 & -0.118 & 0.001 \\ 3.006 & -0.126 & 0.001 \\ 4.063 & -0.176 & 0.002 \\ 5.637 & -0.186 & 0.002 \\ 6.223 & -0.199 & 0.002 \\ 7.050 & -0.224 & 0.002 \\ 7.504 & -0.263 & 0.002 \\ 6.117 & -0.209 & 0.002 \\ 5.951 & -0.205 & 0.001 \\ 4.768 & -0.155 & 0.001 \\ 4.337 & -0.142 & 0.001 \end{Bmatrix}$$

In Fig. 4 dependences of the heat transfer coefficient on time are presented for several segments of the oil pipeline. As is seen from the figure, the values of k change in a wide range:

$$0.4 \le k \le 2.5. \tag{16}$$

This corresponds to the actual picture of the process of heat transfer: the values of k are directly associated with the conditions of heat transfer and the properties of the ground. And since both the conditions and the properties change substantially along the pipeline, the range (16) is also appreciable. The use of the proposed procedure in calculations of the operational conditions of oil pipeline made it possible to increase the accuracy of calculations to 5%.

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