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FEATURES OF DISTRIBUTION OF TEMPERATURE ALONG THE LENGTH OF OIL PIPELINE

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ХАРАКТЕРНЫЕ ОСОБЕННОСТИ РАСПРЕДЕЛЕНИЯ ТЕМПЕРАТУРЫ ПО ДЛИНЕ НЕФТЕПРОВОДА

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oil emulsion, thermal conductivity, heat transfer, friction, viscosity, heat balance, temperature, density, oil pipeline, flow, environment, water concentration, hydraulic resistance, volume rate, gas.

One of the actual challenges in fluid (oil, water and gas) transportation from wells to oil treatment installation is determination of a law of temperature distribution along the length of a pipeline at low ambient temperature. That temperature leads to increase in viscosity and deposition of wax on inner surface of a pipe. To overcome that challenge it is needed to consider several defining characteristics of formation fluid (FF) flow. Complexity of a solution is caused by two factors. From the one hand, in most cases (especially on a late stage of field development) FF is an oil emulsion (OE) that contains gas bubbles. From the other hand, temperature gradient between fluid flow and the environment has significant value (especially in the winter period of the year). At the same time, the higher content of emulsified water droplets (EWD) in OE and lower flow temperature, the higher FF viscosity, and consequently productivity (efficiency) of oil pumping system is reduced. Performed research and analysis of field experimental data showed that a function of oil viscosity versus temperature has a hyperbolic law; a function of OE viscosity versus concentration of EWD has a parabolic one. A heat balance for a certain section of a pipeline in steady state of fluid motion using a method of separation of variables was established taking into account above mentioned factors, Fourier's empirical laws on heat conductivity and Newton's law on heat transfer. As a result, unlike existing works, an exponential law of distribution of temperature along the length of a pipeline is obtained. A law takes into account nonlinear nature of change in viscosity of OE from change in temperature of flow and concentration of water in an emulsion.

Ключевые слова:
нефтяная эмульсия, теплопроводность, теплопередача, трение, вязкость, тепловой баланс, температура, плотность, нефтепровод, поток, окружающая среда, концентрация воды, гидравлическое сопротивление, объемный расход, газ.

Одной из актуальных проблем при перекачке пластового флюида (нефти, воды и газа) от скважин до установки подготовки нефти является определение закона распределения температуры по длине нефтепровода при низкой температуре окружающей среды, приводящей к повышению вязкости и отложению на внутренней поверхности трубы асфальтеносмолопарафинистых веществ. Решение данной проблемы требует учета некоторых определяющих характеристик потока пластового флюида (ПФ). Сложность решения этой задачи заключается в том, что, с одной стороны, в большинстве случаях (особенно на поздней стадии разработки месторождения) ПФ является нефтяной эмульсией, содержащей газовые пузырьки, с другой стороны, градиент температуры между потоком жидкости и окружающей средой имеет существенное значение (особенно в зимний период года). При этом с повышением содержания эмульгированных водяных капель (ЭВК) в нефтяной эмульсии и с понижением температуры потока вязкость ПЖ повышается, и, следовательно, снижается производительность (эффективность) нефтеперекачивающей системы. Проведенные исследования и анализ промысловых экспериментальных данных показали, что изменение вязкости нефти от значения температуры описывается гиперболическим законом, а вязкость нефтяной эмульсии от концентрации ЭВК – параболическим. С учетом этих факторов и эмпирических законов Фурье о теплопроводности, Ньютона о теплопередаче составлен баланс тепла для определенного участка нефтепровода при установившемся режиме движения жидкости с использованием метода разделения переменных. В результате, в отличие от существующих работ, получен экспоненциальный закон распределения температуры по длине нефтепровода, учитывающий нелинейный характер изменения вязкости нефтяной эмульсии в зависимости от изменения температуры потока и концентрации воды в эмульсии.

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Introduction

Low environmental temperature that surround a pipeline from oil production wells to an oil treatment unit leads to increase in viscosity, presipitation of wax on inner walls of a pipeline and as a result to friction head loss. Determination of temperature distribution along a pipeline is one of the important challenges in upstream.

In order to determine friction head loss h_{fr} along a pipeline of round section the Darcy–Weisbach equation is used [1-3]:

$$h_{fr} = \lambda \frac{l}{D}\frac{\vartheta^2}{2\rho} = i \cdot l, \qquad (1)$$

where λ is for coefficient of hydraulic resistance that depends on the Reynolds number and relative roughness of the inner surface of a pipeline; *l* and *D* are for length and diameter of a pipeline, m; ρ is for liquid density, kg/m^3; ϑ is for average speed of liquid flow, m/s.

As a result of friction on elementary section of a pipeline *dz* some work are lost. That work is represented by the equation

$$G_{\text{т}} = \frac{G_{OE}\rho_{OE} gidz}{E}, \qquad (2)$$

where G_{OE}, ρ_{OE} are for volumetric rate, m^3/h, and density, kg/m^3, of oil emulsion respectively; *g* is for gravity, m^2/s; *z* is for distance from oil production wells, m; *E* is for mechanical equivalent of heat (1 kcal = 427 kgs·m = 427·9,81 N·m).

There are formula (2) is used in [1, 4] to determine a degree of liquid distribution along the pipeline. However, this formula does not reflect direct effect of oil viscosity on a temperature value.

If we write heat balance for an elementary section of a pipeline *dz* under steady-state fluid motion and solve a composite differential equation using the method of separation of variables, then we get an exponential function of change of current temperature value versus length of a pipeline, temperature at the beginning of a pipeline and temperature of surrounding environment [1, 4]. However, as it is shown in [1], one of determining factors of fluid flow (oil, water, gas) such as oil viscosity in a pipeline is not considered. The value of this factor is also reinforced by the fact that in real conditions it is not oil, which was the subject of research by the authors of the works [1, 3, 5-13], but a much more complex oil emulsion with a gas mixture flows inside a pipeline from oil production wells to an oil treatment unit. At the same time, flow of mixture and gas in comparison with oil flow leads to additional increase in λ value and h_{fr} consequently.

In order to take into account viscosity solution of a differential equation was done using a simplified method (linear dependence) of change in viscosity from change in a value of current temperature [3].

Challenge statement

Based on the analysis of existing works it follows that establishment of a law for distribution of temperature along a pipeline, taking into account nonlinear character of change in viscosity of an oil emulsion from change in temperature of flow of formation fluid (water, oil and gas) and concentration of water in an oil emulsion as well as initial temperature of flow and temperature of the surrounding environment is an urgent task.

Challenge solution

Our studies and analysis of field experimental data have shown that change in oil viscosity as a function of temperature is described by hyperbolic law

$$\mu_O = \frac{a_1}{b + ct},$$

and viscosity of an oil emulsion is determined by the following equation:

$$\mu_{OE} = \mu_O \cdot \beta = \mu_O \left[1 + sw + \alpha w^2\right] = \frac{a_1\beta}{b+ct} = \frac{a}{b+ct}, \qquad (3)$$

where μ_O, μ_{OE} are for viscosities of oil and oil emulsion respectively, g/(cm·s) (Poise) or 1.019·10^{-4} (kg·s)/m^2 (Pa); *w* is for the concentration of emulsified water droplets in an oil emulsion; a, b, c, s, α are for coefficients determined experimentally; t is for temperature of an oil emulsion, °C.

The amount of heat released from friction of an oil emulsion over a corresponding section of a pipe length dz over the time $d\tau$ is determined by the following equation

$$G_h = \frac{128 G_{OE}^2 \mu_{OE}}{\pi D^4 E} dz \cdot d\tau. \quad (4)$$

The amount of heat lost by flow of an oil emulsion flowing during time $d\tau$ through the area of interest is expressed by the equation [14–16]

$$G_L = G_{OE} \rho_{OE} C_{OE} \frac{dt}{dz} dz \cdot d\tau, \quad (5)$$

where $\rho_{OE} = w\rho_w + (1-w)\rho_O$, $C_{OE} = wC_w + (1-w)C_O$, $\rho_w, \rho_O, \rho_{OE}$ are for the density of water, oil and an oil emulsion respectively, kg/m^3; C_w, C_O, C_{OE} are for specific heat of water, oil and an oil emulsion, kcal/(kg·°C).

Then, using Newton's cooling law [14-16], it is possible to determine amount of heat lost by a pipeline wall in a cooling medium with a temperature t_1 along dz in time $d\tau$ [16–18]:

$$G_{HL} = \pi D K_1 (t - t_1) dz \cdot d\tau, \quad (6)$$

$$K_1 = \lambda_{av} \frac{(t_{wall} - t_1)}{(t_{liq} - t_{wall})\delta}, \quad (7)$$

$$\lambda_{av} = \frac{(\lambda_1 h_O + \lambda_2 h_{wall} + \lambda_3 h_{gr})}{\delta}, \quad (8)$$

where K_1 is for heat transfer coefficient, kcal/(m^2·°C·h); λ_{cp} is for average heat conductivity of an adhesive oil layer (or wax), wall of oil pipeline and layer of soil covering the pipeline, kcal/(m^2·°C·h); t_{wall}, t_1 and t_{liq} are for temperature of a wall of pipeline, the environment and liquid in the pipe respectively, °C; δ is for the total thickness of a near-wall oil layer, a wall of pipe and ground, $\delta = h_O + h_{wall} + h_{gr}$; h_O, h_{wall} and h_{gr} are for thickness of an oil layer, walls of an oil pipeline and soil, m; λ_1, λ_2, λ_3 are for corresponding thermal conductivities of mentioned layers.

In order to determine average flow speed of a liquid in a round circle tube the parabolic Stokes law is used [19-20], i.e.

$$\vartheta = \frac{1}{4\mu_{OE}} \left(\frac{D^2}{4} - r^2 \right) - \left(-\frac{\partial p}{\partial z} \right), \quad (9)$$

where r is for a parameter expressing change in thickness of a liquid from the center of the flow to the wall.

In this case, fluid flow rate G is determined as follows:

$$G = \int_0^{D/2} 2\pi r dr \cdot \vartheta = -\left(\frac{\partial p}{\partial z} \right) \frac{\pi D^4}{128\mu_{OE}}. \quad (10)$$

Taking into account (9) and (10), we obtain

$$G_H = \int_0^{\frac{D}{2}} 2\pi r \frac{\mu_{OE}}{E} \left(\frac{\partial \vartheta}{\partial r} \right)^2 dz d\tau dr = \frac{\pi D^4}{128 \mu_{OE} E} \left(\frac{128^2 G_{OE}^2 \mu_{OE}^2}{(\pi D^4)^2} \right) dz \cdot d\tau = \frac{128 G_{OE}^2 \mu_{OE}}{\pi D^4 E} \cdot dz \cdot d\tau,$$

where p, ϑ are pressure, Pa, and average speed of an oil emulsion flow, m/h; τ is for time, h.

On the basis of the above mentiond, we compose heat balance for an elementary section of a pipe dz under steady-state flow conditions of an oil emulsion:

$$\Delta G = G_H - G_L - G_{HL} = \frac{128 G_{OE}^2 \mu_{OE}}{\pi D^4 E} - G_{OE} \rho_{OE} C_{OE} \frac{dt}{dz} - \pi D K_1 (t - t_1) = 0. \quad (11)$$

To determine distribution (change) of temperature of an oil emulsion flow along the length of a pipeline from oil production wells to an oil treatment unit, integrating the differential equation (11), taking into account formula (1), we obtain

$$J_3 \int \frac{b + ct}{cJ_1 t^2 + J_1 (b - ct_1) t - (bJ_1 t_1 + J_2 a)} dt = -z + c_1, \quad (12)$$

where $J_1 = \pi D K_1$, $J_2 = \frac{128 G_{OE}^2}{\pi D^4 E}$; $J_3 = G_{OE} \cdot \rho_{OE} \cdot C_{OE}$; t, t_1 are for current temperature and temperature surrounding oil pipeline, °C; c_1 is for integration constant; z is for distanve from oil production wells, m.

Taking the notation $cJ_1 = r$; $J_1(b - ct_1) = d$; $bJ_1T_1 + J_2 a = e$, we transform the integral (12) into the following type:

$$J_3 \int \frac{b + ct}{rt^2 + dt - e} dt = -z + c_1. \quad (13)$$

After some transformations the integral (13) looks as follows

$$\frac{J_3}{r} \int \frac{b + ct}{(t + n)(t + m)} dt = -z + c_1. \quad (14)$$

Solution for the integral equation (14) is

$$K_1 \cdot \ln\left[c_1 (t + n)^p \cdot (t + m)^q\right] = -z + c_1. \quad (15)$$

Values of c_1 are estimated for initial conditions $z = 0,\ t = t_0$

$$c_1 = K_1 \ln\left[c_2 (t_0 + n)^p \cdot (t_0 + m)^q\right],$$

where n, m, p, q are for variable coefficients that are determined depending on technological parameters, i.e.

$$n = \frac{1}{2r}\left[d - \left(d^2 + 4re\right)^{1/2}\right],$$

$$m = \frac{1}{2r}\left[d + \left(d^2 + 4re\right)^{1/2}\right],$$

$$p = c_1 n - b,$$

$$q = b - c_1 m,$$

$$K_1 = \frac{1}{r(n - m)},$$

where $d = J_1(b - ct_1)$, $e = bJ_1t_1 + J_2a_2$, $r = cJ_1$.

As a result, we obtain desired equation for dependence of change in temperature of an oil emulsion flow on initial temperature (t_0) and distance along an oil pipeline from oil production wells to the current point (z):

$$(t + n)^p \cdot (t + m)^q =$$

$$= (t_0 + n)^p \cdot (t_0 + m)^q \exp\left(-\frac{z}{J_3 K_1}\right).$$

Thus, calculated values of temperature distribution of an oil emulsion flow along an oil pipeline from oil production wells to an oil treatment unit were determined depending on distance (table).

Calculated values of temperature distribution along an pipeline

w	Z, m								
	0	2000	4000	6000	8000	10 000	12 000	14 000	16 000
0.1	30	28.439	26.957	25.595	24.342	23.191	22.132	21.169	20.264
0.2	30	18.499	13.628	11.566	10.692	10.322	10.165	10.099	10.071

Taking into account calculated values indicated in the table, a graph of change in temperature distribution along a pipeline is built (Fig.)

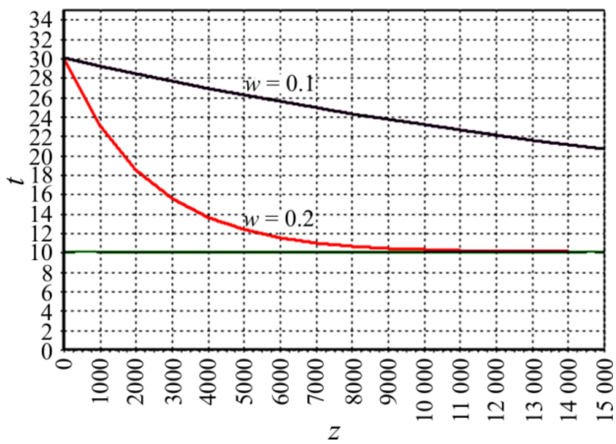

Fig. Change in distribution of temperature along the length of a pipeline

The figure shows that the bigger the length the exponentially smaller the temperature of oil emulsion flow. Herewith, temperature of oil emulsion flow at z = ∞ is equal to temperature of the surrounding oil pipeline environment.

Conclusion

System analysis of modern state of the challenge to determine distribution of temperature of oil flow, oil emulsion and three-phase system oil-water-gas along the length of oil pipeline is performed.

It is shown that existing works on mathematical modelling of change of flow temperature along the length of a pipeline do not consider influence of viscosity of an oil emulsion on distribution of temperature.

Therefore, the authors of the paper propose a hyperbolic law of change of oil viscosity from temperature and parabolic law of change of oil emulsion viscosity depending on concentration of emulsified water droplets in oil.

The mathematical model of distribution of oil flow temperature along the length of an oil pipeline depending on viscosity of an oil emulsion has been developed. That uses empirical law of Fourier on thermal conductivity, Newton's heat transfer law and viscous friction of oil emulsion flow. Calculated results of temperature distribution along a pipeline are presented.

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