Modeling of the Heat and Mass Transfer Process in Assessing the Thermal Effect When Processing an Oil Well with a Hot Coolant Through Hollow Rods

E. Goltsov(✉), N. Kostarev, and N. Trufanova

National Research Polytechnic University, 29, Komsomolsky Avenue, Perm 614990, Russia
evgeny.goltsov@yandex.ru

Abstract. The article considers numerical simulation of the processes of heat and mass transfer in an oil well complicated by asphalt-resin-paraffin deposits, taking into account the heating of the oil fluid flow supplied by the coolant. The results of numerical experiments were obtained by implementing a two-dimensional axisymmetric mathematical model based on the laws of conservation of mass, energy and momentum vector. The numerical investigation was performed in the ANSYS Fluent finite element analysis environment using the finite volume method. The solutions of the equations of stationary turbulent heat and mass transfer in an oil well have been obtained when estimating the thermal effect of hot oil treatment through the hollow rods of the downhole pump. The adequacy of the proposed model has been evaluated. Fields of temperatures and velocities, temperature distribution in the borehole by depth at different modes of coolant feeding are obtained. We calculated the thermal state of the well structure when flushing with liquid through hollow rods with thermal insulation and evaluated the efficiency of the technology and its effectiveness at a given temperature of paraffin melting (60 °C).

Keywords: Heat transfer · Mass transfer · Mathematical model · Ansys Fluent · Coolant · Boreholes · Hollow rods

1 Introduction

When operating oil wells, there are a number of problems associated with the processes of asphalt-resin-paraffin (ARPD) deposition on the walls of the equipment. Efficiency of combating this phenomenon depends on the region, technological parameters of production and the chosen method of thermal effect assessment. It is of practical interest to assess the efficiency of the methods for controlling the ARPD for a particular well. The method of mathematical modeling allows evaluating the efficiency of this or that approach with minimum costs. Thus, the works [1] and [2] consider the wells, where the heating cable is used as a method of combating paraffin deposits, presented a numerical solution of non-stationary problem of heat and mass transfer in an oil well with a heating

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cable. The articles [3] and [4] investigate the influence of electromagnetic radiation on asphalt-resin-paraffin deposits, analyze the dynamics of paraffin deposition and the rate of its removal. The use of hot oil pumped into the well to warm it up to a temperature above the paraffin crystallization temperature is considered in [5]. The paper presents a method for determining the temperature regime in direct and reverse evaluation of the thermal effect when treating a well with a hot thermal fluid based on the thermal balance of the fluid being in the elevator pipes and annulus. Of scientific and practical interest is the method presented in this work, in which the assessment of the thermal effect in the treatment with hot thermal oil well is carried out through the hollow rods of the deep well pump.

2 Main Part

The following study examines a method for estimating the thermal effect of treating an oil well with hot coolant through hollow rods located in a tubing string. Moving along the rods, the coolant heats the wellbore fluid flow, exits through the bypass sleeve, mixes with the main oil flow and rises to the wellhead. Figure 1 shows a general schematic of the equipment for evaluating the thermal effect of treating the well with hot coolant.

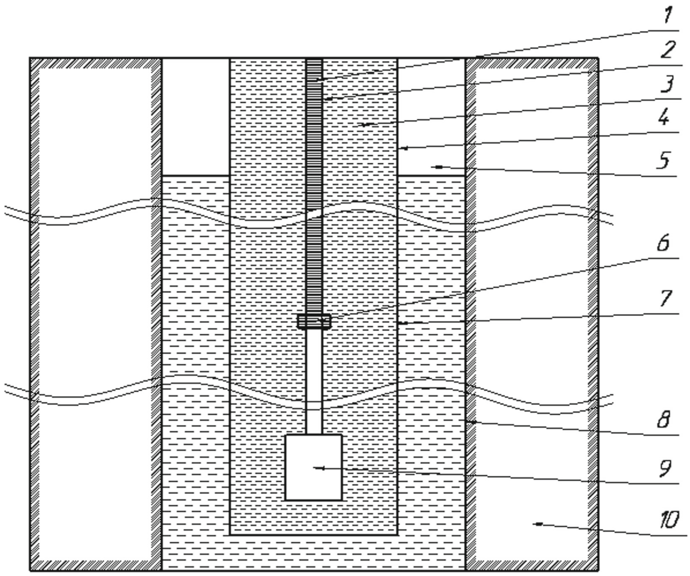

Fig. 1. General scheme of the well and equipment to assess the thermal effect of hot coolant treatment. Structure of equipment: 1 - coolant; 2 - hollow rods; 3 - oil in tubing; 4 - tubing string; 5 - associated oil gas; 6 - transfer flushing sleeve; 7 - tubing; 8 - production string; 9 - pump; 10 - ground mass.

The work considers the section from the wellhead to the flushing sleeve, which is 800 m long. The hollow rod string consists of two parts of different diameters and is located inside the tubing. The following assumptions are made in describing the heat and mass transfer processes: the thermal properties of solid materials do not depend on temperature, the infinite earth mass is replaced by a limited area, the oil fluid is considered as a single-phase medium. We consider a stationary, axisymmetric problem of turbulent heat and mass transfer of oil in the tubing, in the hollow rods and in the annular space. A realizable k-epsilon model from the RANS (Reynolds averaged Navier Stokes equations) family of models is used to describe the turbulent transport. To simulate the turbulent flow in the boundary layer, we use near-wall functions.

The mathematical model of motion and heat transfer in an oil well is based on the laws of conservation of mass, amount of motion and energy, taking into account the assumptions made, has the following form:

Transport equations (Navier–Stokes equations averaged by Reynolds):

$$\begin{gathered}\rho_i(\bar{\upsilon}_{ir}\frac{\partial\bar{\upsilon}_{ir}}{\partial r}+\bar{\upsilon}_{iz}\frac{\partial\bar{\upsilon}_{ir}}{\partial z})=-\frac{\partial\bar{P}_i}{\partial r}+\mu_i\left(\frac{\partial^2\bar{\upsilon}_{ir}}{\partial r^2}+\frac{1}{r}\frac{\partial\bar{\upsilon}_{ir}}{\partial r}+\frac{\partial^2\bar{\upsilon}_{ir}}{\partial z^2}-\frac{\bar{\upsilon}_{ir}}{r^2}\right)+\\ +\frac{1}{r}\frac{\partial}{\partial r}\left(-r\rho_i\overline{\upsilon_{ir}'^2}\right)+\frac{\partial}{\partial z}\left(-\rho_i\overline{\upsilon_{ir}'\upsilon_{iz}'}\right),\end{gathered} \tag{1}$$

$$\begin{gathered}\rho_i(\bar{\upsilon}_{ir}\frac{\partial\bar{\upsilon}_{iz}}{\partial r}+\bar{\upsilon}_{iz}\frac{\partial\bar{\upsilon}_{iz}}{\partial z})=-\frac{\partial\bar{P}_i}{\partial z}+\mu_i\left(\frac{\partial^2\bar{\upsilon}_{iz}}{\partial r^2}+\frac{1}{r}\frac{\partial\bar{\upsilon}_{iz}}{\partial r}+\frac{\partial^2\bar{\upsilon}_{iz}}{\partial z^2}\right)+\\ +\frac{1}{r}\frac{\partial}{\partial r}\left(-r\rho_i\overline{\upsilon_{ir}'\upsilon_{iz}'}\right)+\frac{\partial}{\partial z}\left(-\rho_i\overline{\upsilon_{iz}'^2}\right)\end{gathered} \tag{2}$$

The transport equation for the kinetic energy of turbulence:

$$\begin{gathered}(\frac{\partial\rho_i k\overline{\upsilon}_{ir}}{\partial r}+\frac{\partial\rho_i k\overline{\upsilon}_{iz}}{\partial z})=\frac{\partial}{\partial r}\left[\left(\mu_i+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial r}\right]\\ +\frac{\partial}{\partial z}\left[\left(\mu_i+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right]+G_k+G_b-\rho_i\varepsilon-Y_M\end{gathered} \tag{3}$$

The transfer equation for the rate of dissipation of kinetic energy of turbulence:

$$\begin{gathered}(\frac{\partial\rho_i\varepsilon\overline{\upsilon}_{ir}}{\partial r}+\frac{\partial\rho_i\varepsilon\overline{\upsilon}_{iz}}{\partial z})=\frac{\partial}{\partial r}\left[\left(\mu_i+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial r}\right]+\frac{\partial}{\partial z}\left[\left(\mu_i+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial z}\right]+\rho_i C_1 S\varepsilon\\ -\rho_i C_2\frac{\varepsilon^2}{k+\sqrt{\nu_i\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b\end{gathered} \tag{4}$$

Turbulent viscosity:

$$\mu_t=\rho_i C_\mu\frac{k^2}{\varepsilon} \tag{5}$$

The incompressibility equation:

$$-\rho_i\left(\frac{\partial(r\overline{\upsilon}_{iz})}{\partial z}+\frac{\partial(r\overline{\upsilon}_{ir})}{\partial r}\right)=0 \tag{6}$$

Energy equation for liquid elements:

$$\begin{aligned}&\frac{\partial}{\partial r}\left[\overline{\upsilon}_{ir}(\rho_i E+p)\right]+\frac{\partial}{\partial z}\left[\overline{\upsilon}_{iz}(\rho_i E+p)\right]=\frac{\partial}{\partial r}\left(k_{eff}\frac{\partial T}{\partial r}+\overline{\upsilon}_{ir}(\tau)_{eff}\right)+\\&+\frac{\partial}{\partial z}\left(k_{eff}\frac{\partial T}{\partial z}+\overline{\upsilon}_{iz}(\tau)_{eff}\right)\end{aligned} \tag{7}$$

Energy equation for solid elements:

$$\lambda_j\left(\frac{\partial^2 T}{\partial r^2}+\frac{\partial^2 T}{\partial z^2}\right)=0 \tag{8}$$

The system of differential Eqs. (1–8) was closed by the following boundary conditions: at the inlet to the pump pipe, a velocity plot for oil was set corresponding to the well's flow rate equal to 20 m3/day and the oil temperature at the coupling level equal to 15 °C; a coolant flow velocity plot corresponding to a given flow rate of 150 m3/day and the coolant temperature of 120 °C; at the wellhead, the convective heat exchange condition:

$$q=\alpha\left(T_0-T_{up}\right) \tag{9}$$

A temperature distribution corresponding to a geotherm with a geothermal gradient equal to 0.2 °C/10 m is set on the surface bounding the earth's region:

$$T_{zm}=T(z). \tag{10}$$

The condition of ideal thermal contact was set at the interface of heterogeneous media:

$$T^{(n)}|_{r_i}=T^{(n+1)}|_{r_i},\ \lambda_n\frac{\partial T^{(n)}}{\partial r}\bigg|_{r_i}=\lambda_{n+1}\frac{\partial T^{(n+1)}}{\partial r}\bigg|_{r_i}. \tag{11}$$

For speeds in the center of hollow rods and tubing - the maximum speed condition, and on the walls - the conditions of adhesion and non-penetration.

Differential equations of heat and mass transfer in an oil well can be solved analytically or numerically [6–9]. Problem (1)– (11) was solved numerically by the finite volume method in the ANSYS Fluent software product.

Table 1 describes the properties of materials used in modeling the heat and mass transfer process.

Table 1. Properties of the materials used.

Material	Density ρ, kg/m^3	Heat capacity C, J/(kg·K)	Thermal conductivity λ,W/(m·K)	Viscosity μ, mPa·s
Ground	1900	1680	1.82	-
Steel	8030	502.48	16.27	-
Oil	800	2000	0.15	10
Cement	1400	900	0.85	-
Thermal insulation (compound)	840	1200	0.3	-

3 Results

As a result of a numerical study of the processes of heat and mass transfer of oil and coolant in an oil well with hollow rods, temperature and velocity fields were obtained throughout the entire volume of the studied area. The flow rate of the well in question is 20 m3/day. The melting point of the ASPO varies linearly from the temperature at the mouth equal to 52 °C, to the temperature at a depth of 800 m equal to 59.3 °C. The results are shown in Figs. 2–7.

Figure 2 shows the velocity field in the tubing at 799 m depth of the flow-through socket. The figure shows that the coolant in the center of the rod channel has maximum velocity values, then, leaving the socket, it mixes with the oil flow and continues moving along the tubing. The speed of oil flow with coolant is 2 times lower than the speed of coolant in hollow rods, despite the fact that the flow of coolant is added to the flow of produced oil. The drop in velocity is due to the fact that the cross-sectional area in tubing is significantly larger than in hollow rods.

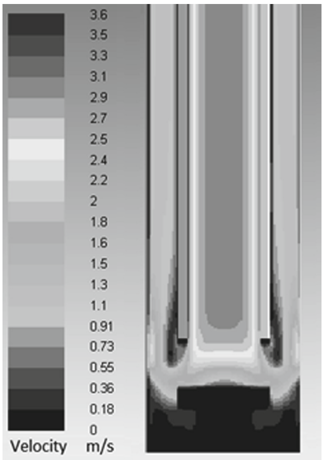

Fig. 2. Velocity field in the tubing for the well section where the coolant exits the flow coupling. The coolant is supplied with a flow rate of 150 m3 / day with a temperature of 120 °C.

Figure 3 shows the temperature fields of a well Sect. 800 m long with different temperatures of the injected coolant. The figure shows the intensity of the change in the temperature of the coolant as it moves along the hollow rods. The higher the initial temperature of the coolant, the higher the temperature of the oil fluid moving through the tubing. The temperature of the coolant itself and the temperature of the metal rods decreases with increasing depth of the well. The maximum oil temperature of 158 °C is reached at the mouth of the tubing channel at a coolant temperature of 210 °C, while the average oil temperature at the height of the tubing is 89 °C.

The effect of coolant flow on the temperature of oil in the tubing is shown in Fig. 4. It is obvious that with an increase in coolant flow, the intensity of well heating increases and the average temperature of oil in the tubing increases from 55 °C to 89 °C with an increase in flow from 150 m^3/day to 250 m^3/day.

The influence of the coolant temperature on the efficiency of assessing the thermal effect when treating a well with a hot coolant is shown in Fig. 5., Fig. 6 shows that even at the temperature of the injected oil equal to 210 °C (curve 1), the temperature at the coupling level (800 m) falls below the melting point of paraffin and is 55 °C. While at a coolant temperature equal to 120 °C, the oil temperature at the same depth is 40 °C (curve 4). Hence, it can be concluded that an increase in the temperature of the coolant at a given flow rate of 150 m^3/day and a well flow rate of 20 m^3/day does not prevent the process of deposition of paraffin on the walls of the tubing or to carry out a full assessment of the thermal effect when treating an oil well with a hot coolant.

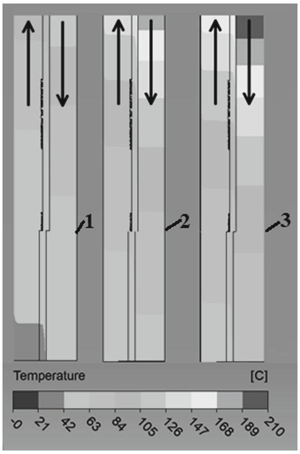

Fig. 3. Temperature fields in tubing for wells with different coolant temperatures: 1 – 120 °C; 2 – 150 °C; 3 – 210 °C.

Analysis of the processes of heat and mass transfer during the flow of oil and coolant at different values of coolant flow allowed us to determine the value of the latter, when using which (250 m^3/day) the oil temperature along the entire length of the well is greater than the melting point of paraffin (curve 5), despite the fact that the temperature of the coolant was set equal to 120 °C Fig. 6., curve 2. In this in this case, the oil temperature at

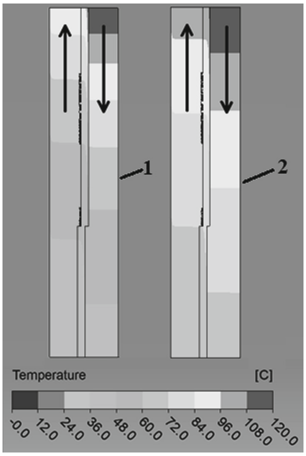

Fig. 4. Temperature fields in the tubing for wells with different coolant flow rates: 1 – 150 m^3/day; 2 – 250 m^3/day.

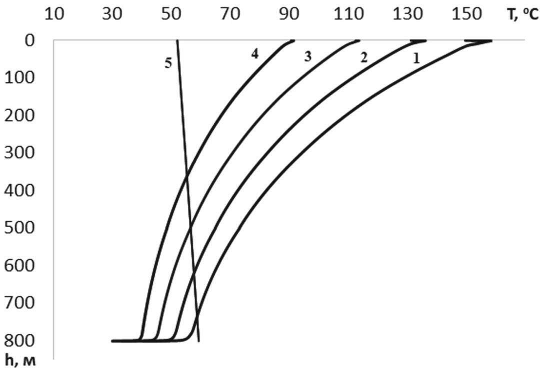

Fig. 5. Temperature distribution on the inner wall of the tubing along the depth at different temperatures of the coolant. The coolant is oil supplied with a flow rate of 150 m^3/day. The flow rate of the well is 20 m^3/day. 1 – the temperature is 210 °C; 2 – the temperature is 180 °C; 3 – the temperature is 150 °C; 4 – the temperature is 120 °C; 5 – the melting point of paraffin.

the coupling level is 62 °C. Thus, under such conditions, the assessment of the thermal effect when treated with a hot coolant, there is a complete removal of paraffin deposits from the walls of the well.

The most effective assessment of the thermal effect of a well with hot oil can be achieved by changing both the temperature of the coolant and its flow rate. The paper considers the case when the temperature of the coolant was set equal to 150 °C, and the flow rate was 200 m^3/day. The temperature distribution on the tubing wall in this mode for assessing the thermal effect during treatment with a hot coolant is shown in Fig. 6. (curve 1). It can be seen from the figure that the temperature along the considered

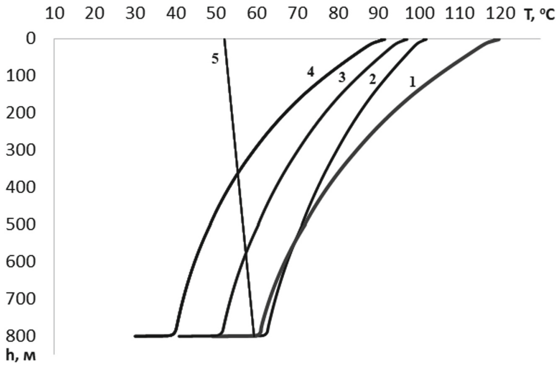

Fig. 6. Temperature distribution on the inner wall of the tubing from the depth at different coolant flow rates. The flow rate of the well is 20 m^3/day. 1 – coolant oil heated to 150 °C and supplied with a flow rate of 200 m^3/day; 2 – coolant oil heated to 120 °C and supplied with a flow rate of 250 m^3/day; 3 – coolant oil heated to 120 °C and supplied with a flow rate of 200 m^3/day; 4 – coolant oil heated to 120 °C and supplied with a flow rate of 150 m^3/day; 5 – the melting point of paraffin.

section does not fall below the melting point of paraffin, therefore, the removal of ASF will occur throughout the entire section.

In order to heat the well more effectively, a thermal insulation layer is applied to the inner surface of the rods Fig. 7. To evaluate the effectiveness of the thermal insulation layer when flushing the well through the hollow rods of a downhole pump, two well models with and without the thermal insulation layer on the inner surface of the hollow rods were implemented. As a result, temperature distribution curves on the inner tubing wall were obtained for both cases.

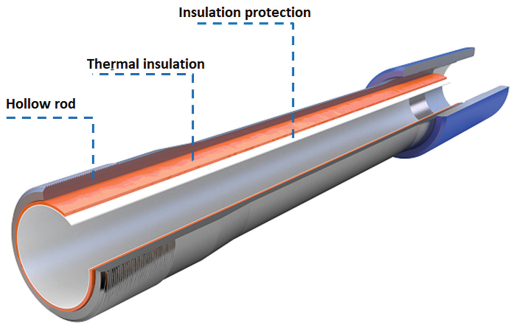

Fig. 7. General view of the boom design.

The calculation results are shown in Fig. 8 and Table 2.

Figure 8 shows that the presence of thermal insulation layer on the inner surface of hollow rods significantly affects the temperature distribution on the tubing wall in the well. With a thermal insulation layer in place, the temperature at the coupling level (1,200 m) reaches 56 °C, an increase of 36 °C compared to the case without thermal insulation. This is due to the fact that the coolant has a higher temperature at the outlet of the coupling equal to 63 °C. Whereas, moving along the rods without thermal insulation, the coolant has time to cool down to 20.7 °C at the coupling level.

According to the results of the conducted studies, the following conclusion can be drawn: when assessing the thermal effect when treating a well with a coolant supplied through hollow rods, the coolant flow has a more significant effect than its temperature, however, for the most effective assessment of the thermal effect, it is necessary to vary the values of both of these parameters.

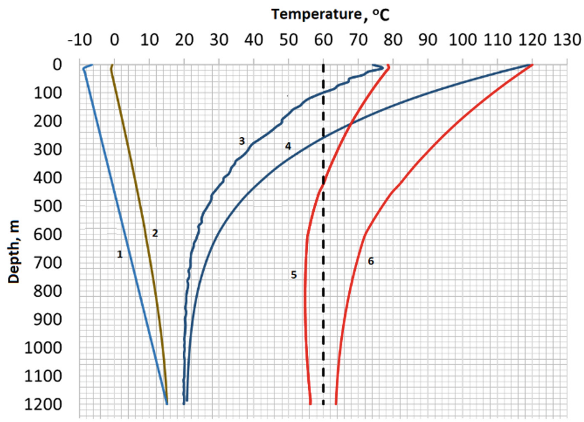

Fig. 8. Temperature distribution on the inner wall of the tubing and inside the rods by depth for the cases with and without thermal insulation. The heat-transfer agent is oil, supplied at a flow rate of 150 m^3/day and a temperature of 120 °C for 5 h. Paraffin crystallization temperature is assumed to be 60 °C.1 – geotherma; 2 - without flushing; 3 - without tubing insulation; 4 – without insulation rod; 5 - with tubing insulation; 6 - with rod insulation.

Table 2. Comparison of flushing performance with and without thermal insulation.

Boom design	Indicators		
	Flow temperature at the coupling level, °C	Depth of complete removal of ARPD, m	Depth of the most probable ARPD removal area, m
With insulation	56	424	1200
Without insulation	20	109	424

4 Conclusion

This paper shows how the efficiency of heat treatment of an oil well with a coolant through hollow rods of a deep pump depends on the parameters of the coolant supply. The influence of the flow rate and temperature of the coolant on the temperature distribution in the well column is estimated. The presence of a thermal insulation layer significantly increases the efficiency of flushing the well with hot coolant through the hollow rods.

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