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Simulation and automation of thermal processes in oil well

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Abstract. The paper presents a two-dimensional mathematical model and a numerical analysis of heat and mass transfer processes in an oil well. The proposed and implemented mathematical model of the process of heat and mass transfer in an oil well allows analyzing the temperature field in the whole space of an oil well and is suitable for any fields equipped with an electric centrifugal pump. Temperature and velocity fields were obtained, as well as the distribution of temperature on the wall of the pump tubing along the depth of the well. On the basis of the obtained temperature fields, the modes of periodic heating of the well by the heating cable were developed. Recommendations are given on the choice of power parameters and the time of warming up the well.

1. Introduction

At the present time, when oil wells are operating, the problem of the formation of asphalt, resin, and paraffin deposition on the internal surfaces of the pipe walls during the motion of the oil fluid arises. Paraffin deposits significantly reduce the efficiency of the well until its complete failure, and also increase equipment wear [1, 2]. One of the ways to combat asphalt, resin, and paraffin deposition is warming up a section of the borehole exposed to paraffin deposition by heating the cable [3]. Practical interest is the development of the most efficient and economical operating mode of the heating cable, at which the well operates, not complicated by paraffin deposits while minimizing energy costs.

2. Statement of the problem.

The longitudinal section of a well of 2000m depth is considered [4]. The well design is shown in Figure 1. The mathematical model of motion and heat transfer in an oil well is based on the laws of conservation of mass, momentum and energy [5, 6]. The following assumptions were made: the design is flat, nonstationary, the laminar flow, the thermophysical properties of solid materials do not depend on temperature, an infinite mass of earth is replaced by a bounded region.

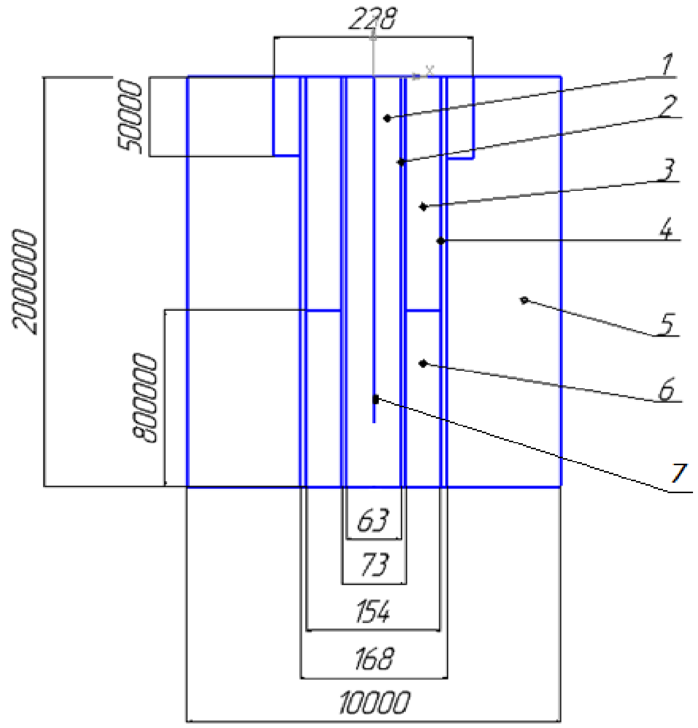

Figure 1. Oil well construction: 1-petroleum liquid, which is extracted by a tubing; 2- tubing; 3-air in the annulus; 4- casing column; 5-soil surrounding the well; 6-oil fluid in the annulus; 7-heating cable.

Taking into account the assumptions made, the system of differential equations has the form:
Continuity equation:

$$-\rho_i\left(\frac{\partial U_{i}x}{\partial x}+\frac{\partial U_{i}y}{\partial y}\right)=k\left(\frac{\partial \rho_i}{\partial t}+U_{i}x\frac{\partial \rho_i}{\partial x}+U_{i}y\frac{\partial \rho_i}{\partial y}\right), \quad (1)$$

Motion equation:

$$\rho_i\left(\frac{\partial U_{i}x}{\partial t}+U_{i}x\frac{\partial U_{i}x}{\partial x}+U_{i}y\frac{\partial U_{i}x}{\partial y}\right)=-\frac{\partial P_i}{\partial x}+\mu_i\left(\frac{\partial^2 U_{i}x}{\partial x^2}+\frac{\partial^2 U_{i}x}{\partial y^2}\right), \quad (2)$$

$$\rho_i\left(\frac{\partial U_{i}y}{\partial t}+U_{i}x\frac{\partial U_{i}y}{\partial x}+U_{i}y\frac{\partial U_{i}y}{\partial y}\right)=-\frac{\partial P_i}{\partial y}+\mu_i\left(\frac{\partial^2 U_{i}y}{\partial x^2}+\frac{\partial^2 U_{i}y}{\partial y^2}\right)+k\beta\left(T-T_0\right)g, \quad (3)$$

where k is the coefficient, which is 0 for oil, and 1 - for air.

The energy equation for an oil fluid:

$$\rho_i\left(\frac{\partial T}{\partial t}+U_x\frac{\partial T}{\partial x}+U_y\frac{\partial T}{\partial y}\right)=\frac{\lambda_i}{c_i}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+Q, \quad (4)$$

the energy equation for air:

$$\rho_i c_i \left(\frac{\partial T}{\partial t} + U_x \frac{\partial T}{\partial x} + U_y \frac{\partial T}{\partial y} \right) = \lambda_i \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right); \quad (5)$$

$$\rho_1(T) = \rho_0 \left[1 - \beta(T - T_0) \right]. \quad (6)$$

The air density is determined by the Boussinesq law.

Equation of thermal conductivity for solid elements of the well design:

$$\lambda_i \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) = c_i \rho_i \left(\frac{\partial T}{\partial t} \right), \quad (7)$$

where *x*, *y*, are Cartesian coordinates; *i,* is index of study areas, *i=1* is air, *i=2* is oil, *i=3* is tubing, *i=4* is casing column, *i=5* is cement, *i=6* is ground; $U_{i\,x}$, $U_{i\,y}$ are velocity vector components; T is temperature; t is time; P_i is pressure; ρ_i is density; μ_i is viscosity; c_i is specific heat; λ_i is thermal conductivity; β is thermal expansion coefficient of air; Q is heat generated by the heating cable.

The system of differential equations (1) - (7) is supplemented by the following boundary conditions: on the surface bounding the earth's area, a temperature corresponding to the geothermal is given:

$$T|_{ground} = T(h). \quad (8)$$

At the interface between different media, the heat fluxes and temperatures are equal:

$$T^{(n)}|_{x_i} = T^{(n+1)}|_{x_i}, \quad (9)$$

$$\lambda_n \left. \frac{\partial T^{(n)}}{\partial x} \right|_{x_i} = \lambda_{n+1} \left. \frac{\partial T^{(n+1)}}{\partial x} \right|_{x_i}. \quad (10)$$

For speeds in the center of the well, the condition for the maximum speed is given, and on the tubing wall the conditions for adhesion and non-penetration:

$$U_y\big|_{x=0} = U_{y\max}, \quad (11) \qquad U_y\big|_{x=x_{wall}} = 0, \quad (12) \qquad U_x\big|_{x=x_{wall}} = 0. \quad (13)$$

At the bottom of the well, the bottomhole temperature (T=100 ^{o}C) and the velocity diagram corresponding to a flow rate of 40 tons/day are set; in the wellhead, the temperature at the surface of the earth is set equal to 3 ^{o}C and the steady-state flow regime [7].

Properties of the materials of the well, oil and air components are given in Table 1.

Table 1. Properties of materials.

Material	Density ρ, kg/m^3	Specific heat C, j/(kg°K)	Thermal conductivity λ W/(m°K)	Viscosity μ kg/(m·s)
Ground	1900	1680	1.82	-
Cement	1400	900	0.85	-
Steel	8030	502.48	16.27	-
Oil	743.5	2000	0.15	0.01
Air	1.225	1006.43	0.0242	1.78e-05

In this work, the cable is located in the center of the tubing from the wellhead to the start of the possible paraffin deposit. The beginning of the site was taken at a depth of 201 meters, it is at this depth that the temperature of the oil on the wall of the compressor tub pump reaches the crystallization temperature of the paraffin adopted at 40 ° C [8, 9]. The cable is an internal heat source with a diameter of 20 mm, the heat output from the cable was calculated according to the law of Joule-Lenz.

3. Results of the study

The problem (1) - (13) was solved numerically by the finite element method. For calculations ANSYS Fluent was used.

Well heating can be carried out in a constant and periodic mode of supply of thermal power. With constant mode, the cable is switched on all the time and constantly heats the well. This method is less economical than the periodic mode [10].

In more detail, the periodic mode of operation was considered, which is an alternation of switching on and off the heating cable. In the course of solving a non-stationary two-dimensional mathematical model of heat and mass transfer in an oil well, taking into account the heating cable with different heating power, the following results were obtained:

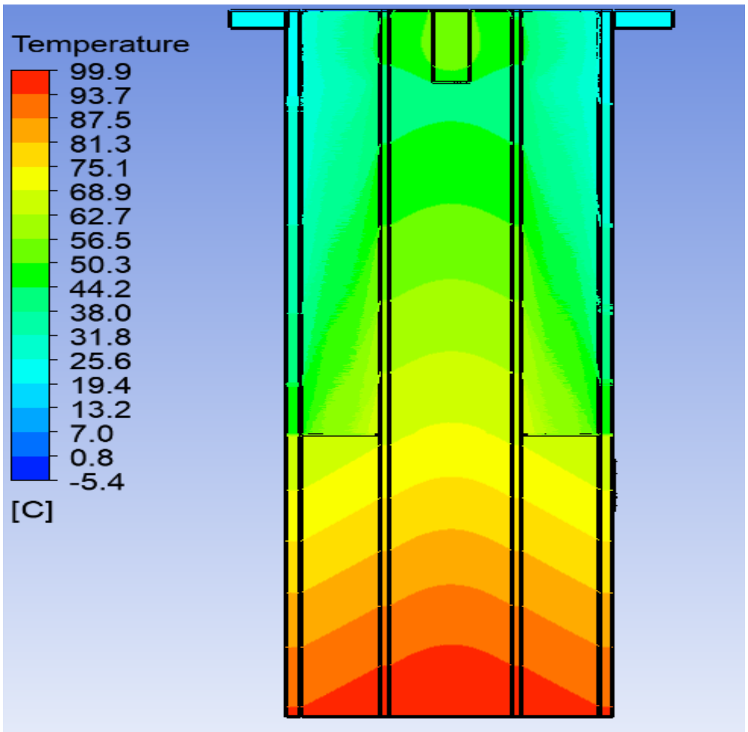

Figure 2. Temperature field of oil well with cable included.

It can be seen from figure 2 that for the output to the stationary mode for all the heating options, the required time was about 14 hours, after which it can be considered that the well is warmed up. For the case of a cable operating at a power of 2.5 kW / m^3, the temperature at the outlet of the tubing is at 45 ° C, and for a cable operating at a power of 7.5 kW / m^3, the temperature is set at about 62 ° C. The study has chosen the mode of heating the well with a cable operating at a power of 7.5 kW / m^3.

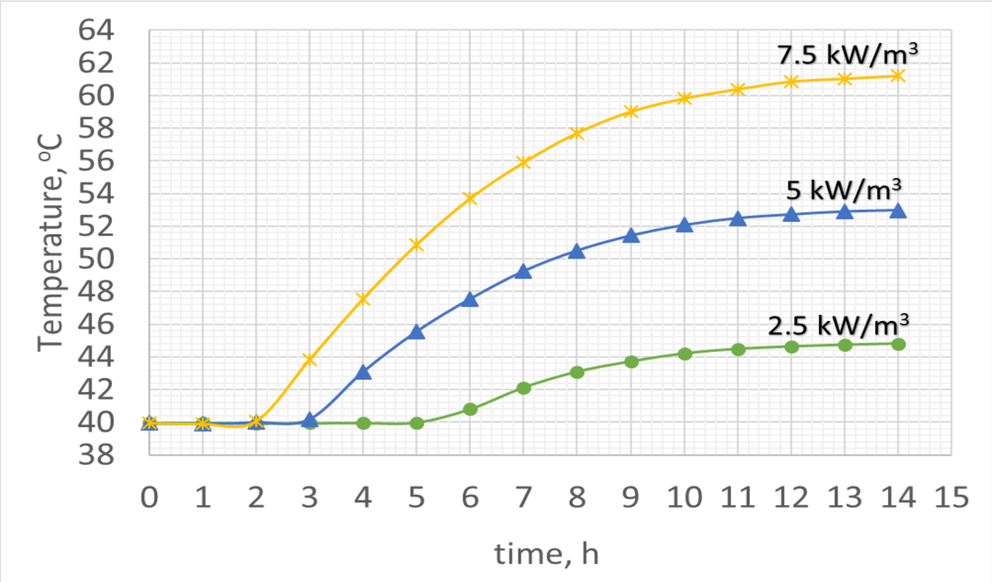

Figure 3. Dependence of temperature on the inner wall of the tubing at the wellhead of the heating time for modes with different heating capacities.

To determine the parameters of the periodic well heating regime, the effect of different heating times was investigated. Three cases of heating cable operation - switching on for 3, 4 and 6 hours are considered, after which the cable was switched off until the temperature in the wellhead became equal to the temperature of paraffin crystallization. The voltage was then applied to the cable again with the same heating time and the cycle was repeated. As a result, temperature dependences were obtained on the pipe wall in time, as shown in figure 4.

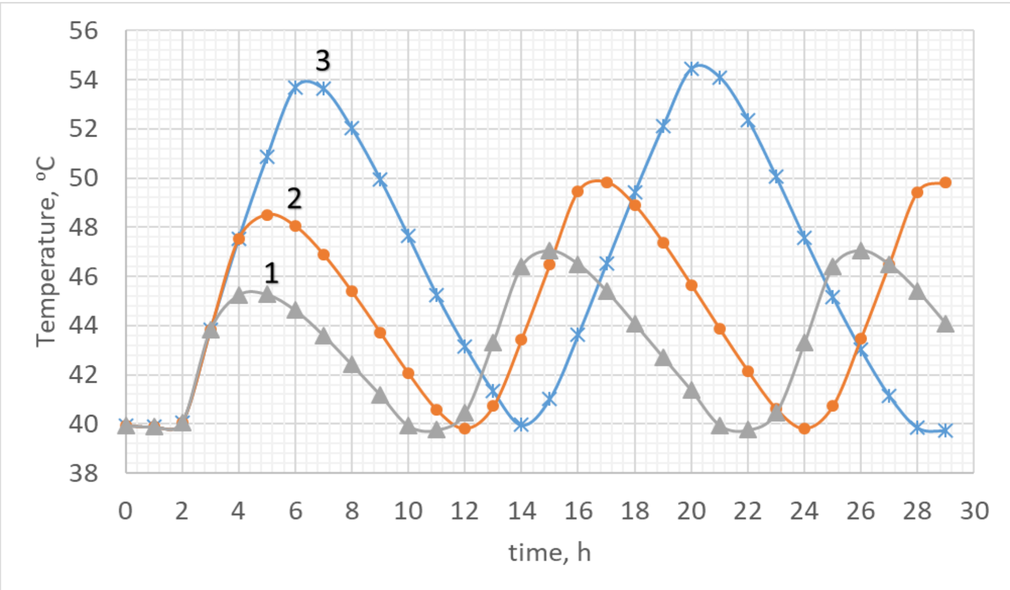

Figure 4. Dependence of temperature on the inner wall of the tubing at the wellhead of the heating time for wells with different heating cable operating time. 1 - the heating time is 3 hours; 2 - the heating time is 4 hours; 3 - the heating time is 6 hours. Heating power is 7,5 kW / m^3.

In all three cases, despite the different heating times, the well cools down about 8 hours, therefore, it is more economical to use a three-hour heating mode of the well. In the six-hour mode, the cable is turned on and off for 24 hours for two days. Moreover, with a three-hour mode for two days, the cable will be on for 15 hours and 33 hours off, which reduces the amount of energy consumed. This cycle of work does not allow the deposition of paraffin since the temperature does not fall below the crystallization temperature.

4. Conclusion

The developed model allows one to obtain the temperature field of the well, to determine the length of the site of possible precipitation of deposits of asphalts, resins, and paraffins at the stage of well design. This makes it possible to take measures to prevent the formation of deposits of asphalts, resins, and paraffins in a previously known area, which will significantly reduce the cost of developing deposits. With the help of the developed model, it is possible to estimate the influence of the heating cable in the fight against paraffin deposits as well as to choose the most efficient and economical modes of cable operation.

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