Numerical implementation of the mathematical model of combined effect on the formation using FORTRAN programming language

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Abstract. The main method of high-viscosity oil production is heating, but there are difficulties in delivering heat to the formation and distributing this heat there quite evenly. The existing methods of delivering heat to the formation are often ineffective – small heat coverage area, excessively high temperatures in some places, loss of a large amount of heat from the wellhead to the bottomhole, need for large areas around the well for thermal action. Combined electromagnetic-acoustic action with the injection of solvent onto the formation could significantly increase the effectiveness of formation heating. The study solves the problem of finding a temperature field with a two-stage effect on the formation: electromagnetic-acoustic heating and then pumping solvent into the formation in order to increase the radius of coverage with thermal impact. With this setting of the problem, the resulting mathematical model does not have an analytical solution. A numerical solution using the finite difference method with an implicit scheme gives fairly accurate results.

1. Introduction
One of the promising methods to develop high-viscosity oil and natural bitumen fields, which is more efficient compared to traditional heat exposure technologies, is the method of high-frequency electromagnetic (HF EM) field treatment on the bottomhole zone of the formation. The method has a number of advantages that exclude restrictions on the use of other methods of thermal exposure [4]. At the same time, the application of electromagnetic heating of oil formation in combination with acoustic field and with injection of solvent into the formation allows increasing the formation heating zone due to the convective transfer of heat together with solvent. Thus, the combination of methods improves the efficiency of heat treatment and leads to new problems of mathematical physics containing a system of equations of electrodynamics, hydrodynamics and thermodynamics. The complexity of these problems is aggravated by the presence of nonlinearity of differential equations, the dependence of fluid viscosity and thermal conductivity of the medium on the temperature and power of emitters of electromagnetic and
acoustic fields and a variety of practical conditions. There is a cycle of new topical problems related to the field of fluid mechanics and thermodynamics of the interaction of the emitter with the substance [5, 6].

2. Problem Statement
The study considers the two-stage impact on the formation. At the 1st stage the combined action of high-frequency electromagnetic and acoustic fields on the oil formation is performed without extraction of the formation fluid. At the 2nd stage the oil formation is exposed to HF EM field and at the same time solvent is pumped into it. With this method of influencing the formation, the bottomhole zone at the 1st stage is strongly heated due to thermal sources created by absorbing energy of EM and acoustic waves by the medium, and increased effective thermal conductivity of the medium due to the acoustic effect on the formation. At the 2nd stage, heat accumulated in the bottomhole zone of the formation is carried away by the injected solvent far into the formation [9]. Besides, due to the fact that EM waves are transmitted to the formation from the ground HF generator through well pipes (tubing and casing), which are used as a coaxial transmission line, the solvent enters the formation already in a heated state. It is believed that the solvent is injected into the formation using tubing [7, 10].

In setting the problem, we accept the following assumptions, which describe geometric and thermophysical characteristics of the formation and the filtered fluid:

1) The oil formation is finite, has the shape of a coaxial cylinder (internal radius coincides with the radius of the well, external – with the radius of the boundary);
2) The well is perfect in terms of the degree and nature of penetration;
3) At the 2nd stage of the impact, the filtration rate of the solvent mixture and oil is determined from Darcy’s equation:

\[ v = \frac{k \cdot \hat{P}}{\mu_{m}} \]  

where \( \mu_{m} \) – dynamic viscosity of the oil and solvent mixture determined from the Kendall formula:

\[ \ln \mu_{m} = C_{1} \ln \mu_{1} + C_{2} \ln \mu_{2} \] 

The viscosity of the mixture components depends on the temperature and is determined from the expression:

\[ \mu_{j} = \mu_{j0} \exp\left(-\gamma_{j} \Delta T\right) \]  

where \( \mu_{j0} \) – initial viscosity (at temperature \( T=T_{0} \)); \( \gamma_{j} \) – temperature coefficient; \( \Delta T=T-T_{0} \).

4) At the 1st stage of the impact on the formation at the initial moment of time the temperature in the formation at all points is the same:

\( T(r,0) = T_{0} \) 

At the 1st stage of the impact on the formation, as in the problem solved in the 2nd section of the proposed work, only the thermal conductivity equation is solved. Unlike the 2nd section, in this case there is no convective member in the thermal conductivity equation, since it is not produced simultaneously with the HF impact of the formation-fluid drainage. So, the equation solved at the 1st stage is as follows:

\[ \frac{\partial T}{\partial t} = \frac{1}{C_{p} \cdot r} \frac{\partial}{\partial r}\left( r \lambda_{a} \frac{\partial T}{\partial r} \right) + \frac{q_{a}}{C_{p}} \] 

where \( q_{a} \) – total heat sources created due to EM and acoustic effects on the formation; \( \lambda_{a} \) – thermal conductivity coefficient, \( C_{p} \) – volumetric heat capacity of formation rocks.

At the 2nd stage of the impact on the formation, a system of equations of piezococonductivity, thermal conductivity and diffusion is solved [1, 3, 4]:
\[ \frac{\partial P}{\partial t} = k_1 \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{r}{\mu_{cm}} \frac{\partial P}{\partial r} \right) \quad \text{with} \quad k_1 = \frac{k}{m\beta_{cm} + \beta_0} \quad (6) \]

\[ \frac{\partial T}{\partial t} = \frac{1}{C_p} \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda_0 r \frac{\partial T}{\partial r} \right) - \frac{\nu_{cm} \rho_{cm} c_{cm} \partial T}{C_p} \frac{\partial T}{\partial r} + \frac{q_s}{C_p} \quad (7) \]

\[ m \frac{\partial C_j}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( D_r \frac{\partial C_j}{\partial r} \right) - \frac{\nu_{cm}}{} \frac{\partial C_j}{\partial r} \quad (8) \]

\[ D = \delta(D_0 + \lambda \nu) \quad (9) \]

Here, \( j = 1, 2 \) – component indices for solvent and oil, respectively; \( P \) – pressure; \( C_j \) – concentration of components, \( C_1 + C_2 = 1 \); \( D \) – coefficient of convective diffusion; \( m, k \) – porosity and permeability of formation; \( \beta_{cm}, \beta_0 \) – compressibility coefficients of mixture and rock skeleton; \( \epsilon_{cm}, \rho_{cm} \) – heat capacity, density of mixture of oil and solvent; \( D_0 \ll \lambda \nu \) – molecular diffusion coefficient; \( \lambda \) – dispersion parameter of the porous medium; \( \delta \) – empirical coefficient, the value of which depends on the presence of the EM field power, in the absence of the field \( \delta = 1 \). A solution is sought regarding \( C_1 \).

The boundary conditions at the bottom of the well and at the boundary of the formation have the form for temperature at the 1st stage:

\[ \frac{\partial T(r_{1s}, r)}{\partial r} = 0 \quad \text{and} \quad \frac{\partial T(r_{1s}, t)}{\partial r} = 0 \quad (10) \]

At the 2nd stage of the impact on the formation, the temperature reached at the 1st stage is initial for the 2nd stage. The pressure at all points of the formation at the beginning of the 2nd stage is the same and equal to the formation pressure, the concentration of solvent at all points of the formation at the beginning of the 2nd stage is zero. At the boundary of the formation, the pressure is equal to the initial formation pressure \( P_0 \), the heat flow is equal to zero, and the concentration of solvent is equal to zero:

\[ P(r, 0) = P_0; P(r_{1s}, t) = P_i; C_1(r, 0) = 0; C_1(r_{1s}, t) = 0. \quad (11) \]

At the well radius the pressure is equal to the bottomhole pressure \( P_b \), the bottomhole temperature \( T_b \) is associated with the temperature of the injected solvent \( T_k \) and energy losses in the EM wave transmission line, the concentration of the solvent is equal to one:

\[ P(r, 0) = P_0; P(r_{1s}, t) = P_b; C_1(r, 0) = 0; C_1(r_{1s}, t) = 0. \quad (11) \]

\[ P(r_{1s}, t) = P_b; T(r_{1s}, t) = T_{bs}; C_1(r_{1s}, t) = 1. \quad (12) \]

When calculating the heating of the solvent moving into the tubing to the bottom of the well it is assumed that partially the energy released into the tubing heats the rocks surrounding the well. Another part is spent on heating the solvent. In this case, the temperature value, to which the solvent is heated, is determined by the expression:

\[ T_s = T_c + \frac{W}{c_s \rho_s \varepsilon_s}, \quad W = 0.225 \left( \frac{N_e - N_{e0}}{\alpha_1 + \alpha_2} \right) \quad (13) \]

where \( c_s, \rho_s, \varepsilon_s \) – specific heat capacity, density and flow rate of the solvent injected into the formation, \( W \) – energy lost in the well, \( N_{e0}, N_e \) – power of the EM wave emitter and power of the EM wave generator located on the earth’s surface; \( \alpha_1, \alpha_2 \) – coefficient of attenuation of EM waves in coaxial pipes of the well, \( H \) – depth of the productive layer.

The absorption coefficients of EM waves in casing and tubing may be determined by the expressions [2]:
\[ \alpha_1 = \frac{R_s}{2Z \ln(R_1 / R_2)} \cdot \frac{1}{R_2}, \quad R_s^2 = \frac{\sigma \mu}{\mu \alpha}, \quad \alpha_2 = \frac{R_s}{2Z \ln(R_3 / R_2)} \cdot \frac{1}{R_3}, \quad Z^2 = \frac{\mu_a}{\varepsilon_0}, \] (14)

where \( R_s \) – active surface resistance of pipes, \( Z \) – wave resistance of air in the annulus; \( R_2 \) – external radius of tubing pipes; \( R_3 \) – внутренний радиус труб НКТ; \( R_1 \) – inner radius of casing pipes; \( \sigma \mu \) – absolute magnetic permeability of well pipes; \( \sigma \) – specific electrical conductivity of well pipes.

The finite difference method was applied to solve the system of equations (1) – (14), the used running scheme – implicit. Let the axis along the coordinate \( r \) be divided into \( N \) equal parts, thus the spatial pitch is uniform. Let us denote in step \( l \) by the spatial coordinate \( r \), and in step \( \tau \) – by time. The indices of nodes by coordinate \( r \) are indicated as \( i \), by time \( j \).

Equation (5) is written in a finite difference form:

\[ \frac{T_{i}^{j+1} - T_{i}^{j}}{\tau} = \frac{1}{C_p r_i} \left( \frac{\lambda_{a,i} r_i^2}{l^2} \frac{T_{i+1}^{j+1} - T_{i}^{j+1}}{l^2} - \frac{\lambda_{a,i} r_i^2}{l^2} \frac{T_{i-1}^{j+1} - T_{i}^{j+1}}{l^2} \right) + \frac{q_{a,i}}{C_p} \]

or

\[ A T_{i}^{j+1} - C_i T_{i}^{j+1} + B T_{i}^{j+1} = -F_{i}^{j}, \] (15)

where

\[ A_i = \frac{\tau \lambda_{a,i} r_i^2}{C_p r_i^2 l^2}; \quad B_i = \frac{\tau \lambda_{a,i} r_i^2}{C_p r_i^2 l^2}; \quad C_i = 1 + A_i + B_i; \quad F_{i}^{j} = T_{i} - \frac{\tau q_{a,i}}{C_p} \]

The boundary conditions (10) for temperature in a finite difference form:

\[ T_{0}^{j+1} = \kappa_1 \cdot T_{i}^{j+1} + \mu_1; \quad \kappa_1 = 1; \quad \mu_1 = 0; \] \[ T_{N}^{j+1} = \kappa_2 \cdot T_{N-1}^{j+1} + \mu_2; \quad \kappa_2 = 1; \quad \mu_2 = 0. \] (16)

Running formulas for solving a problem:

\[ T_{i}^{j+1} = \alpha_{i} T_{i}^{j+1} + \beta_{i}, \quad i = N-1, N-2, \ldots, 1, 0; \] (17)

\[ \alpha_{i} = \frac{B_i}{C_i - \alpha_i A_i}, \quad \beta_{i} = \frac{A_i \beta_{i+1} + F_{i+1}}{C_i - \alpha_i A_i}, \quad i = 1, 2, \ldots, N-1. \] (18)

Comparing the formula \( T_{0}^{j+1} = \alpha_{i} T_{i}^{j+1} + \beta_{i} \) with the boundary condition (16), we find:

\[ \alpha_i = \kappa_i = 1; \quad \beta_i = \mu_i = 0. \]

The diffusivity equation (6) in finite differences will be as follows:

\[ \frac{P_{i}^{j+1} - P_{i}^{j}}{\tau} = \frac{k_i}{r_i} \left( \frac{P_{i}^{j+1} - P_{i+1}^{j+1}}{\mu_{cm,i} r_{i+1}^2 l^2} - \frac{P_{i}^{j+1} - P_{i-1}^{j+1}}{\mu_{cm,i} l^2} \right) \]

or, if led to the same summands:

\[ A_{p,j} P_{i}^{j+1} - C_{p,j} P_{i}^{j+1} + B_{p,j} P_{i+1}^{j+1} = -F_{p,j}^{j} \] (19)

where

\[ A_{p,j} = \frac{\tau k_i}{r_i \mu_{cm,i} l^2}; \quad B_{p,j} = \frac{\tau k_i}{r_i \mu_{cm,i} l^2}; \quad C_{p,j} = 1 + A_{p,j} + B_{p,j}; \quad F_{p,j}^{j} = P_{i}^{j} \]

The boundary conditions (11) for pressure in a finite-difference form:
\[ P_{i}^{j+1} = \kappa_{p,i} \cdot P_{i}^{j+1} + \mu_{p,i}; \quad \kappa_{p,i} = 0; \quad \mu_{p,i} = P_{i} \quad \text{(20)} \]

Running formulas:

\[ P_{i}^{j+1} = \alpha_{p,i} P_{i}^{j+1} + \beta_{p,i+1}, \quad i = N - 1, N - 2, \ldots, 1, 0; \quad \text{(21)} \]

\[ \alpha_{p,i} = \frac{B_{p,i}}{C_{p,i} - \alpha_{p,i} A_{p,i}}, \quad \beta_{p,i} = \frac{A_{p,i} B_{p,i} + F_{p,i}}{C_{p,i} - \alpha_{p,i} A_{p,i}}, \quad i = 1, 2, \ldots, N - 1. \quad \text{(22)} \]

Comparing the formula \( P_{0}^{j+1} = \alpha_{p,1} P_{1}^{j+1} + \beta_{p,1} \) with the boundary condition (21), we find \( \alpha_{p,1} = \kappa_{p,1} = 0; \quad \beta_{p,1} = \mu_{p,1} = P_{0} \).

The thermal conductivity equation with the convective member (7) in finite differences will be:

\[ \frac{T_{i}^{j+1} - T_{i}^{j}}{\tau} = \frac{\lambda_{b}}{C_{p,i} r_{i}^{2}} \left( r_{i+1/2} \frac{T_{i+1}^{j} - T_{i}^{j}}{r_{i+1/2}^{2}} - r_{i-1/2} \frac{T_{i}^{j} - T_{i-1}^{j}}{r_{i-1/2}^{2}} \right) - \frac{v_{cm,i} C_{cm} \rho_{cm}}{C_{p}} \frac{T_{i+1}^{j} - T_{i}^{j}}{r_{i+1/2}^{2}} + \frac{q_{b,i}}{C_{p}}, \]

Similar to the above expression, the finite-difference equation is divided by indices:

\[ A_{T,i} T_{i}^{j+1} - C_{T,i} T_{i}^{j+1} + B_{T,i} T_{i}^{j+1} = -F_{T,i}^{j}. \quad \text{(23)} \]

where

\[ A_{T,i} = \frac{\tau \lambda_{b} r_{i+1/2}^{2}}{C_{p} r_{i}^{2}} + \frac{\tau v_{cm,i} r_{i+1/2}^{2} C_{cm} \rho_{cm}}{C_{p}}, \quad B_{T,i} = \frac{\tau \lambda_{b} r_{i+1/2}^{2}}{C_{p} r_{i}^{2}}, \quad C_{T,i} = 1 + A_{T,i} + B_{T,i}; \quad F_{T,i}^{j} = T_{i}^{j} + \frac{q_{b,i}}{C_{p}}. \]

The boundary conditions (12), (13) for temperature in a finite-difference form:

\[ T_{0}^{j+1} = \kappa_{T,1} \cdot T_{1}^{j+1} + \mu_{T,1}; \quad \kappa_{T,1} = 0; \quad \mu_{T,1} = T_{b} = T_{e} + \frac{W}{c_{e} \rho_{e} g_{e}}; \quad \text{(24)} \]

\[ T_{N}^{j+1} = \kappa_{T,N} \cdot T_{N-1}^{j+1} + \mu_{T,N}; \quad \kappa_{T,N} = 1; \quad \mu_{T,N} = 0. \]

Running formulas to solve the problem (3.25):

\[ T_{i}^{j+1} = \alpha_{T,i} T_{i}^{j+1} + \beta_{T,i+1}, \quad i = N - 1, N - 2, \ldots, 1, 0; \quad \text{(25)} \]

\[ \alpha_{T,i+1} = \frac{B_{T,i}}{C_{T,i} - \alpha_{T,i} A_{T,i}}, \quad \beta_{T,i+1} = \frac{A_{T,i} B_{T,i} + F_{T,i}}{C_{T,i} - \alpha_{T,i} A_{T,i}}, \quad i = 1, 2, \ldots, N - 1. \quad \text{(26)} \]

Comparing the formula \( T_{0}^{j+1} = \alpha_{T,1} T_{1}^{j+1} + \beta_{T,1} \) with the boundary condition (24), we find:

\[ \alpha_{T,1} = \kappa_{T,1} = 0; \quad \beta_{T,1} = \mu_{T,1} = T_{b} = T_{e} + \frac{W}{c_{e} \rho_{e} g_{e}}. \]

The diffusion equation (8) in a finite-difference form:

\[ \alpha_{T,i+1} = \frac{B_{T,i}}{C_{T,i} - \alpha_{T,i} A_{T,i}}, \quad \beta_{T,i+1} = \frac{A_{T,i} B_{T,i} + F_{T,i}}{C_{T,i} - \alpha_{T,i} A_{T,i}}, \quad i = 1, 2, \ldots, N - 1. \]
\[
m\frac{C_{i+1}^j - C_i^j}{\tau} = \frac{1}{r_i} \left( r_{i+\frac{1}{2}} D_{i+\frac{1}{2}} \frac{C_{i+1}^j - C_{i+1}^{j+1}}{l^2} - r_{i-\frac{1}{2}} D_{i-\frac{1}{2}} \frac{C_i^{j+1} - C_{i-1}^{j+1}}{l^2} \right) - v_i \frac{C_i^{j+1} - C_{i-1}^{j+1}}{l}
\]

The finite difference equation is divided by indices:

\[
A_{C,i} C_{i-1}^{j+1} - C_{C,i} C_i^{j+1} + B_{C,i} C_{i+1}^{j+1} = -F_{C,i}^j,
\]

where

\[
A_{C,i} = \frac{\tau D_{i+\frac{1}{2}} r_{i+\frac{1}{2}}}{ml^2} + \frac{\tau D_{i-\frac{1}{2}} r_{i-\frac{1}{2}}}{ml^2}; \quad B_{C,i} = \frac{\tau D_{i+\frac{1}{2}} r_{i+\frac{1}{2}}}{ml^2}; \quad C_{C,i} = 1 + A_{C,i} + B_{C,i}; \quad F_{C,i}^j = C_i^j.
\]

The boundary conditions (11), (12) for solvent concentration in a finite-difference form:

\[
C_0^{j+1} = \kappa_{C,1} \cdot C_1^j + \mu_{C,1}; \quad \kappa_{C,1} = 0; \quad \mu_{C,1} = 1;
\]

\[
C_N^{j+1} = \kappa_{C,2} \cdot C_{N-1}^j + \mu_{C,2}; \quad \kappa_{C,2} = 0; \quad \mu_{C,2} = 0.
\]

Running formulas to solve the problem (27):

\[
C_i^{j+1} = \alpha_{C,i} C_{i+1}^{j+1} + \beta_{C,i+1}, \quad i = N-1, N-2, \ldots, 1, 0;
\]

\[
\alpha_{C,i} = \frac{B_{C,i}}{C_{C,i} - \alpha_{C,i} A_{C,i}}, \quad \beta_{C,i+1} = \frac{A_{C,i} \beta_{C,i} + F_{C,i}}{C_{C,i} - \alpha_{C,i} A_{C,i}}, \quad i = 1, 2, \ldots, N-1
\]

Comparing the formula \(C_0^{j+1} = \alpha_{C,1} C_1^{j+1} + \beta_{C,1}\) with the boundary condition (28), we find: The calculation of the obtained running formulas was carried out using the FORTRAN programming language. The source code of the program is shown in Figure 1.

Fig. 1. Calculation program using FORTRAN language

The result is displayed as a text file. Below is the calculation at specific parameters of impact and oil formation [1, 2].
3. Results and discussion

At the 1st stage of the impact, the following medium parameters were adopted: \( T_0 = 120 \, ^\circ \text{C} \); \( f_\text{f} = 13.56 \, \text{MHz} \); \( e = 7.5 \); \( \tan \delta = 0.05 \); \( \alpha_\text{f} = 0.0194 \, \text{m}^{-1} \); \( \beta_\text{f} = 0.778 \, \text{m}^{-1} \); \( \lambda_\text{f} = 1.28 \, \text{W/(m} \cdot \text{K)} \); \( A = 0.000352 \, \text{m} \cdot \text{K} \); \( f_\text{a} = 22 \, \text{kHz} \); \( \alpha_\text{a} = 0.4758 \, \text{m}^{-1} \); \( C_\text{p} = 1378000 \, \text{J/(m}^3 \cdot \text{K)} \); \( h = 8 \, \text{m} \); \( \rho_0 = 0.05 \, \text{m} \); \( N_\text{f0} = 0 \) and 10 kW; \( N_\text{a0} = 40 \, \text{kW} \).

Temperature distributions at various times are shown in Figure 2.

![Figure 2](image)

Fig. 2. Temperature field distribution in the formation at the 1st stage (a) and at the 2nd stage (b). \( N_\text{a0} = 40 \) kW; \( N_\text{f0} = 10 \) kW; \( P_\text{b} = 15 \, \text{MPa} \) (solid lines) and \( N_\text{f0} = 0 \) (dashed lines);

1 – \( t = 5 \) days; 2 – \( t = 10 \) days; 3 – \( t = 15 \) days; 4 – \( t = 20 \) days; 5 – \( t = 25 \) days, 6 – \( t = 35 \) days.

The temperature distributions shown in the figure demonstrate that the simultaneous acoustic EM exposure greatly changes the temperature distribution in the formation. Temperatures near the well are much higher, since the attenuation coefficient of EM waves by power (\( \alpha_\text{f} = 0.0388 \, \text{m}^{-1} \)) is an order of magnitude less than the attenuation coefficient of acoustic waves by power (\( \alpha_\text{a} = 0.4758 \, \text{m}^{-1} \)).

At the 2nd stage of exposure the calculations were carried out at the following medium parameters in addition to the above parameters for the 1st stage of exposure:

- \( m = 0.3 \);
- \( k = 5 \times 10^{-13} \, \text{m}^2 \);
- \( Z = 376.8 \, \text{Ohm} \);
- \( H = 700 \, \text{m} \);
- \( \beta_\text{f} = 10^{-10} \, \text{Pa}^{-1} \);
- \( \beta_\text{a} = 10^{-10} \, \text{Pa}^{-1} \);
- \( R_0 = 0.03015 \, \text{m} \);
- \( R_1 = 0.05015 \, \text{m} \);
- \( \mu_\text{f0} = 3.418 \times 10^{-8} \, \text{H/m} \);
- \( \alpha_\text{f} = 3.4 \times 10^{-8} \, \text{Ohm}^{-1} \cdot \text{m}^{-1} \);
- \( c_\text{f} = 2057 \, \text{J/(kg} \cdot \text{K)} \);
- \( \rho_\text{f} = 769 \, \text{kg/m}^3 \);
- \( \rho_\text{a} = 918 \, \text{kg/m}^3 \);
- \( c_\text{a} = 2024 \, \text{J/(kg} \cdot \text{K)} \);
- \( \lambda = 1.28 \, \text{W/(m} \cdot \text{K)} \);
- \( C_\text{p} = 1378000 \, \text{J/(m}^3 \cdot \text{K)} \);
- \( \Delta = 0.01 \, \text{m} \);
- \( \mu_\text{f0} = 1.73 \cdot 10^{-5} \, \text{Pa} \cdot \text{s} \);
- \( \mu_\text{a0} = 0.2 \, \text{m} \);
- \( \gamma_1 = 0.0128 \, \text{K}^{-1} \);
- \( \gamma_2 = 0.042 \); \( 0.064 \, \text{K}^{-1} \).

Figure 2 (b) shows how the solvent injection in step 2 affects the temperature distribution in the formation. At \( P_\text{b} = 15 \, \text{MPa} \), \( N_\text{f0} = 20 \, \text{kW} \), \( N_\text{a0} = 10 \, \text{kW} \) the heating zone increases by 1.5-2 times, where oil viscosity decreases.

Besides, as shown in Figure 2 (b), the injection of solvent results in redistribution of the temperature field in the formation thus making it more uniform in space, while the temperature at the bottom of the well is halved compared to the effect without injection of solvent, which in practice will prevent negative consequences associated with overheating of the well bore [10-12].
4. Conclusion

Numerical modeling of the most complex systems of equations allows solving the most time-consuming problems associated with many nonlinear cross-effects. The method of finite-difference schemes in solving differential equations is quite often used due to simplicity and versatility. This paper provides a solution to the problem using FORTRAN.

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