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АНАЛИТИЧЕСКАЯ МОДЕЛЬ ТЕМПЕРАТУРНОГО ПОЛЯ В НЕОДНОРОДНОМ ПЛАСТЕ

ANALYTICAL MODEL OF TEMPERATURE FIELD IN HETEROGENEOUS RESERVOIR

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Аннотация. В статье представлено аналитическое решение задачи о нестационарном температурном поле при фильтрации жидкости в неоднородном по проницаемости пласте. Целью работы была разработка и обоснование упрощенной аналитической модели неизотермической однофазной фильтрации жидкости в пласте с радиальной неоднородностью.
Аналитическое решение для температурного поля в пласте после изменения дебита получено методом характеристик. При решении сделаны два допущения: не учитываются радиальная теплопроводность и сжимаемость насыщенной пористой среды. Аналитические модели сравниваются с численным решением задачи. Показано, что влияние радиальной теплопроводности и сжимаемости для нефте- и водонасыщенных пластовых систем на нестационарное температурное поле после изменения дебита незначительно.
На основе разработанной модели по кривым изменения температуры после изменения дебита можно решать обратную задачу об оценке радиуса зоны нарушения проницаемости в пласте. В статье приведен подробный алгоритм для решения обратной задачи. Возможность реализации данной методики демонстрируется на модельных кривых изменения температуры.

Ключевые слова: температура, давление, фильтрация, конвекция, теплопроводность, баротермический эффект, пласт, скважина, изменение дебита, неоднородный пласт.

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Annotation. The paper studies the problem of unsteady temperature field in heterogeneous reservoir during fluid filtration. The aim of this work was to develop and provide rationale for simplified analytical model of non-isothermal single-phase fluid filtration in heterogeneous reservoir. Analytical solution for the temperature field in the formation after flow rate change is obtained by the method of characteristics. Two assumptions were made in solving the problem: radial thermal conduction and compressibility of saturated porous medium are ignored. Analytical models are compared with the numerical solution of the problem. Radial heat conduction and compressibility of oil- or water-saturated reservoirs influence insignificantly on the unsteady temperature field after the flow rate changes.
It is possible to solve the inverse problem on the evaluation of the damage zone radius of the permeability in the reservoir basing on the model curves of the temperature change after flow rate change. The paper gives a detailed algorithm for solving the inverse problem. The possibility of that method realization is demonstrated on model curves of the temperature change.

Keywords: temperature, pressure, filtration, convection, thermal conduction, compressibility, barothermal effect, reservoir, well, heterogeneous reservoir.

Introduction. Recently there has been increasing interest in the study of wells with autonomous sensors of pressure and temperature [2]. Such approach to study makes it possible to detect the change in pressure and temperature in time and explore layers of transient conditions when the well test [2, 3]. Usually, only the data about pressure changes are used in the quantitative interpretation of the well test. Data of the temperature sensing can be used as an additional independent source of information about the reservoir characteristics. A series of papers and patents are dedicated to methodology of interpretation and research method of thermometry [2, 4, 5–11].

Paper [2] offers a method of multilayer wells study. This method involves the registration of pressure and temperature changes on the top and the bottom of each productive formation during the transition conditions. Such method of well testing requires only one operation of flow rate change at the wellhead for obtaining interpretable data of pressure and temperature in the transition regime. The inverse problem is solved using the regression algorithm of Levenberg – Marquardt.

Patents [5–11] present the possible practical applications of non-stationary thermometry data. It is possible to determine: influx profile, flow rates of the different productive layers in multilayer well and param-

eters of near wellbore zone: permeability and skin factor. The solution of inverse problems involves the numerical simulation of the wellbore temperature.

Paper analyses the problem of unsteady temperature field in the reservoir after flow rate changes. The aim of this work was to develop and provide rationale for simplified analytical model of non-isothermal single-phase fluid filtration in heterogeneous reservoir.

Mathematical Statement

The non-isothermality of flow is due to radial thermal conductivity and the barothermal effect.

Assumptions for reservoir – horizontal, porous, heterogeneous permeability, contains a slightly compressible single-phase fluid.

Following equation describes the change of temperature in reservoir due to convection, heat conduction and barothermal effect [1]

$$C_{res}\frac{\partial T}{\partial t}+C_f v(r,t)\frac{\partial T}{\partial r}=\frac{\lambda}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)-C_f\varepsilon v(r,t)\frac{\partial p}{\partial r}+\phi C_f\eta\frac{\partial p}{\partial t}, \quad (1)$$

where C_{res}, C_f are volumetric heat capacities of the reservoir and the fluid J/(m$^3\cdot$K); T is reservoir temperature, K; r is the radial coordinate, the distance in the reservoir from the wellbore axis, m; t is time, s; v is velocity of fluid flow filtration, m/s; λ is thermal conductivity of the reservoir, W/(m·K); ε, η are the Joule-Thomson coefficient and the adiabatic coefficient for the fluid, K/Pa; ϕ is reservoir porosity (decimal fraction), p is pressure, Pa.

At the initial point of time, the temperature is the same everywhere in the reservoir

$$T(r,0)=T_{res}. \quad (2)$$

Condition at the external boundary

$$T(R,t)=T_{res}, \quad (3)$$

R – reservoir radius, m; T_{res} – is the initial reservoir temperature, K.

The boundary condition on the sandface ($r = r_w$)

$$-\lambda\frac{\partial T}{\partial r}\bigg|_{r=r_w}=\alpha\left(T_w(t)-T\big|_{r=r_w}\right), \quad (4)$$

where T_w – is mean wellbore temperature, K; α – is the thermal exchange coefficient, W/(m$^2\cdot$K).

To describe the pressure field in a reservoir, we use a one-dimensional diffusion equation for the axial symmetry case

$$\beta^*\frac{\partial p}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{k(r)}{\mu}\frac{\partial p}{\partial t}\right) \quad (5)$$

$$\beta^*=\phi\beta^f+\beta^{sk}, \quad (6)$$

where β^* – total compressibility, 1/Pa; β^f, β^{sk} – fluid compressibility and pore compressibility, 1/Pa; k – permeability, m^2; μ – is viscosity of the fluid, Pa·s.

At the initial point of time, the pressure is the same everywhere in the reservoir and equals to the reservoir pressure

$$p(r,0)=P_{res} \quad (7)$$

and at the outer boundary of the reservoir, the pressure remains equal to the reservoir pressure

$$p(R,t)=P_{res}. \quad (8)$$

The boundary condition on the sandface, taking into account the presence of skin factor, is then

$$p_w(t)=p(r_w,t)-S\left(r\frac{\partial p}{\partial r}\right)_{r=r_w}, \quad (9)$$

where p_w – borehole pressure (or bottom-hole), Pa; r_w – wellbore radius, m; S – is the sandface skin factor.

Borehole pressure at the initial point of time

$$p_w(0) = P_w. \tag{10}$$

Transition process for the wellbore pressure is modeled by the following equation

$$Q(t) = 2\pi\left(r\sigma(r)\frac{\partial p}{\partial r}\right)_{r=r_w} - C_s\frac{dp_w}{dt}, \tag{11}$$

where $Q(t)$ is the well flow rate, m^3/s; σ is reservoir transmissibility, $m^3/(Pa\cdot s)$; C_s is wellbore storage effect, m^3/Pa.

$$\sigma(r) = \frac{k(r)h}{\mu}, \tag{12}$$

h is thickness of the reservoir, m.

Thus, we have the following mathematical model that can be divided into two problems for temperature and pressure

$$\begin{cases} C_{res}\dfrac{\partial T}{\partial t} + C_f v(r,t)\dfrac{\partial T}{\partial r} = \dfrac{\lambda}{r}\dfrac{\partial}{\partial r}\left(r\dfrac{\partial T}{\partial r}\right) - C_f\varepsilon v(r,t)\dfrac{\partial p}{\partial r} + \phi C_f\eta\dfrac{\partial p}{\partial t} \\ T(r,0) = T_{res} \\ T(R,t) = T_{res} \\ -\lambda\left.\dfrac{\partial T}{\partial r}\right|_{r=r_w} = \alpha\left(T_w(t) - T|_{r=r_w}\right) \end{cases} \tag{13}$$

The required $v(r, t)$ and $p(r, t)$ are solutions of the boundary-value diffusivity problem

$$\begin{cases} \beta^*\dfrac{\partial p}{\partial t} = \dfrac{1}{r}\dfrac{\partial}{\partial r}\left(r\dfrac{k(r)}{\mu}\dfrac{\partial p}{\partial t}\right) \\ p(r,0) = P_{res} \\ p(R,t) = P_{res} \\ p_w(t) = p(r_w,t) - S\left(r\dfrac{\partial p}{\partial r}\right)_{r=r_w} \\ p_w(0) = P_w \\ Q(t) = 2\pi\left(r\sigma(r)\dfrac{\partial p}{\partial r}\right)_{r=r_w} - C_s\dfrac{dp_w}{dt} \end{cases} \tag{14}$$

The problem (13) – (14) in this form does not have an analytical solution, so it was solved numerically by using the control volumes method for temperature [12]. The radial coordinate grid is uneven. Coordinates of control volumes are related by the ratio: $r_i = \theta r_{i-1}$, $\theta = \left(\dfrac{R}{r_w}\right)^{\frac{1}{N-1}}$ (i is the index corresponding to the node of the control volume, N is the number of nodes).

Simulator is developed on the basis of the numerical model. The simulator calculates the model curves of pressure change and temperature change depending on the reservoir parameters for variable flow rate [13].

Analytical solution

The following assumptions were made to have an analytical solution for problem (13) – (14):

- radial heat conduction is neglected (λ = 0);
- fluid and reservoir pore are incompressible ($\beta^* = 0$);
- influence of wellbore processes for reservoir pressure is neglected ($C_s = 0$);
- sandface skin-factor is neglected, $p_w(t) = p(r_w, t)$.

Given these assumptions the temperature field in the reservoir is described by the following task

$$\begin{cases} \dfrac{\partial T}{\partial t} + u(r,t)\dfrac{\partial T}{\partial r} = -\varepsilon u(r,t)\dfrac{\partial p}{\partial r} + \eta^* \dfrac{\partial p}{\partial t} \\ T\big|_{t=0} = f(r) \end{cases} \tag{15}$$

$$u(r,t) = cv(r,t) = -c\frac{k}{\mu}\frac{\partial p}{\partial r} \tag{16}$$

$$\eta^* = \phi\frac{C_f}{C_{res}}\eta \tag{17}$$

$$c = \frac{C_f}{C_{res}} \tag{18}$$

Problem (15) is solved by the method of characteristics. The characteristics $r(t, r_1)$ are the solution of the next problem

$$\begin{cases} \dfrac{dr}{dt} = u(r,t) \\ r\big|_{t=0} = r_1 \end{cases}. \tag{19}$$

The temperature along the characteristics calculate by the formula [14]

$$T(r(t,r_1),t) = f(r_1) + \varepsilon[P_{res} - p(r(t,r_1),t)] + (\varepsilon + \eta^*)\int_0^t \frac{\partial p(r(\tau,r_1),\tau)}{\partial \tau}d\tau \tag{20}$$

The pressure distribution $p(r, t)$, $\dfrac{\partial p}{\partial r}$, $\dfrac{\partial p}{\partial t}$ and $u(r,t)$ are solution of the problem (14), which, taking into account the accepted assumptions above takes a simpler form

$$\begin{cases} \dfrac{\partial}{\partial r}\left(r\dfrac{k(r)}{\mu}\dfrac{\partial p}{\partial r}\right) = 0 \\ p(r,0) = P_{res} \\ p(R,t) = P_{res} \\ Q(t) = 2\pi\left(\sigma(r)r\dfrac{\partial p}{\partial r}\right)_{r=r_w} \end{cases}. \tag{21}$$

Suppose that the permeability distribution and flow rate is described by piecewise-constant functions

$$k(r) = \begin{cases} k_1, & r \le r_d \\ k_2, & r > r_d \end{cases} \tag{22}$$

$$Q(t) = \begin{cases} Q_1, & t \le t_p \\ Q_2, & t > t_p \end{cases} \tag{23}$$

Production during the time t_p at flow rate is Q_1, after this the flow rate becomes Q_2. The reservoir permeability k_2, and in the near wellbore zone k_1.

Then, according to (21), the pressure distribution when production at flow rate is Q_1 ($t < t_p$) is calculate by the formula

$$p_1(t)=\begin{cases} P_{w1}+\dfrac{Q_1}{2\pi\sigma_1}ln\dfrac{r}{r_w}, & r\le r_d \\ p_1(r_d)+\dfrac{Q_1}{2\pi\sigma_2}ln\dfrac{r}{r_d}, & r>r_d,\ r\le R \\ P_{res}, & r>R \end{cases}. \tag{24}$$

Pressure distribution when production at flow rate is Q_2 ($t > t_p$) is calculate by the formula

$$p_2(t)=\begin{cases} P_{w2}+\dfrac{Q_2}{2\pi\sigma_1}\ln\dfrac{r}{r_w}, & r\le r_d \\ p_2(r_d)+\dfrac{Q_2}{2\pi\sigma_2}\ln\dfrac{r}{r_d}, & r>r_d,\ r\le R \\ P_{res}, & r>R \end{cases} \tag{25}$$

r_d – damage radius of near wellbore zone, σ_1 – near wellbore zone transmissibility ($r \le r_d$) и σ_2 – far zone transmissibility ($r > r_d$), P_{w1} и P_{w2} – borehole pressure for production at flow rates Q_1 и Q_2.

$$P_{w1}=P_{res}-\frac{Q_1}{2\pi\sigma_2}\left(\ln\frac{R}{r_w}+S_d\right) \tag{26}$$

$$P_{w2}=P_{res}-\frac{Q_2}{2\pi\sigma_2}\left(\ln\frac{R}{r_w}+S_d\right) \tag{27}$$

$$S_d=\left(\frac{k_2}{k_1}-1\right)\ln\frac{r_d}{r_w}\ . \tag{28}$$

Then

$$u(r,t)=\begin{cases} -c\dfrac{Q_1}{2\pi h}\dfrac{1}{r}, & t\le t_p \\ -c\dfrac{Q_2}{2\pi h}\dfrac{1}{r}, & t>t_p \end{cases} \tag{29}$$

and

$$\frac{\partial p}{\partial t}=\left(p_1(r)-P_{res}\right)\delta(t)+\left(p_2(r)-p_1(r)\right)\delta\left(t-t_p\right). \tag{30}$$

Taking into account (29), (30), based on (20) it is easy to obtain formula for sandface temperature after change the flow rate

$$T(r_w,t)=f(r_{T2})+\varepsilon\left[p_1(r_{T2})-P_{w2}\right]-\left(\varepsilon+\eta^*\right)\cdot\left[p_1(r_{T2})-p_2(r_{T2})\right], \tag{31}$$

where

$$r_{T_2}=\sqrt{r_w^2+c\frac{Q_2\left(t-t_p\right)}{\pi h}} \tag{32}$$

$$f(x)=T_{res}+\varepsilon\left[P_{res}-p_1(x)\right]-\left(\varepsilon+\eta^*\right)\left[P_{res}-p_1(r_{T1})\right] \tag{33}$$

$$r_{T_1}=\sqrt{x^2+c\frac{Q_1t_p}{\pi h}} \tag{34}$$

The correctness of the analytical solutions are verified by comparison with the results of numerical solution of (13) and (14), with account taken assumptions for the analytical model. Production from a homogeneous reservoir for variable production rate is simulated. Standard deviation (SD) did not exceed 10^{-4} K.

Analysis of the results of simulation

A) *Influence of thermal conductivity and compressibility to temperature*

Temperature change is simulated numerically and analytically for production from water-saturated and oil-saturated reservoir. Thermal conductivity ($\lambda \neq 0$) and compressibility ($\beta^* \neq 0$) of reservoir were taken into account during numerical simulation.

Simulation parameters: well radius 0.1 m; reservoir radius 100 m; wellhead flow rate 100 m^3/day for 10 hours and 50 m^3/day at a later time; the initial pressure in the well and in the reservoir 200 atm; parameter of wellbore storage effect 0 m^3/Pa; initial temperature in the reservoir 20 °C; reservoir permeability 100 md; reservoir porosity 0.2; thickness 5 m; pore compressibility $2 \cdot 10^{-10}$ 1/Pa; rock thermal conductivity 2 W/(m·K); rock heat capacity 800 J/(kg·K); rock density 2200 kg/m^3.

Table 1 – Parameters of the saturating fluid reservoir

Parameter	Water	Oil
Joule-Thomson coefficient, K/Pa	$2 \cdot 10^{-7}$	$4 \cdot 10^{-7}$
Adiabatic coefficient, K/Pa	$3 \cdot 10^{-8}$	$1.4 \cdot 10^{-7}$
Heat capacity, J/(kg·K)	4150	2000
Density, kg/m^3	1000	800
Viscosity, Pa·s	10^{-3}	10^{-2}
Compressibility, 1/Pa	$4 \cdot 10^{-10}$	$15 \cdot 10^{-10}$
Thermal conductivity, W/(m·K)	0.55	0.14

The thermal conductivity of fluid saturated reservoir was calculated with the Lichtenecker model [15]

$$\lambda = \lambda_{sk}^{1-\phi} \lambda_f^{\phi} \tag{35}$$

The thermal conductivity and the compressibility of reservoir in the analytic model are zero.

Water-saturated reservoir

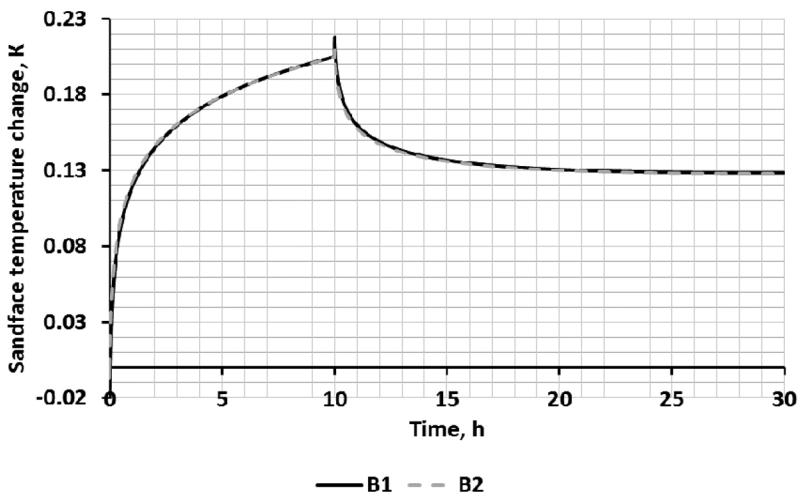

Figure 1 – Sandface temperature changes for water-saturated reservoir: B1 – analytical model, B2 – numerical model

Figure 1 shows that the numerical simulation results and analytical model calculations are practically the same. Slight impact of the compressibility, which lasts less than two hours, appears in the initial period of the production (Figure 2). SD before changes of flow rate 0.0017 K, after changing flow rate SD was 0.0010 K.

Figure 3 shows the results of numerical simulation (considering the thermal conductivity and compressibility) and they are equal by analytical model. The magnitude of the temperature change on the numerical model is slightly higher results of the calculation of the analytical model. This effect for oil saturated reservoir is shown more than in the case of water-saturated reservoir. It is explained by the influence of the compressibility of reservoir, the compressibility of oil is almost four times more than compressibility of water. RMS before changes production rate 0.149 K, and after changing production rate SD was 0.012 K.

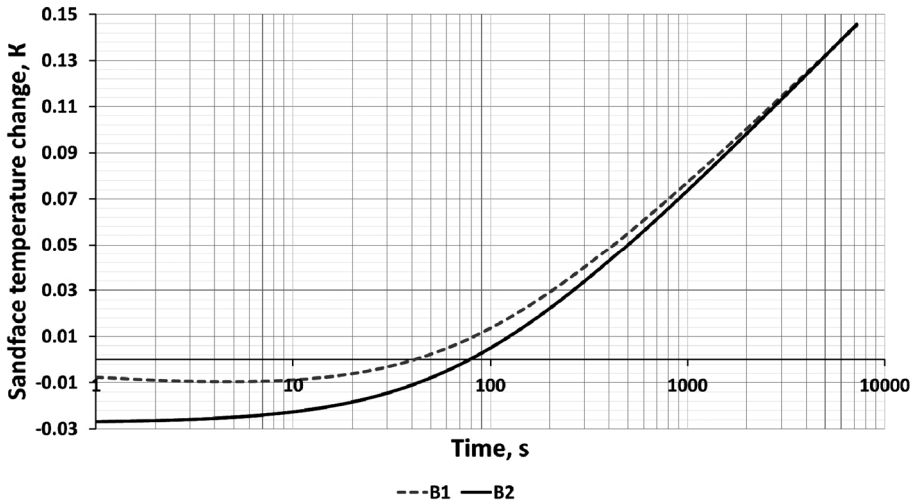

Figure 2 – Sandface temperature changes ($T–T_{res}$) for inflow period from the water-saturated reservoir. Symbols as in Figure 1

Oil-saturate reservoir

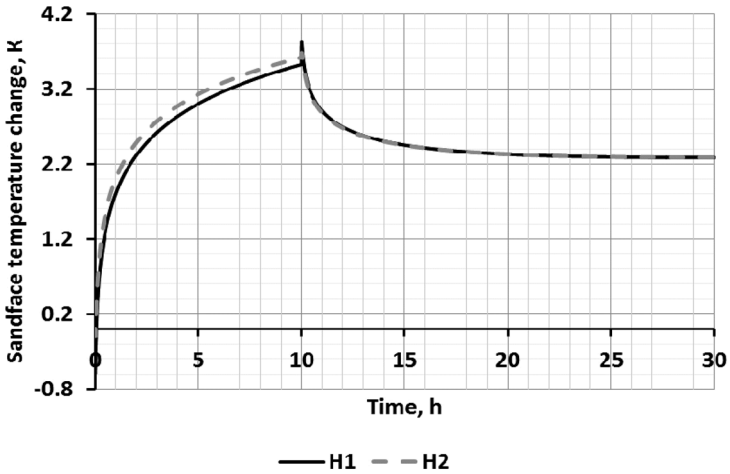

Figure 3 – Sandface temperature changes for the oil-saturated reservoir: H1 – analytical model, the H2 – numerical model

B) *Filtration in homogeneous and heterogeneous reservoir*

The temperature in long production wells varies slightly with time and thus to probe the reservoir by temperature changes is difficult. The easiest way to achieve the temperature change – is to change flow rate.

Case with a variable flow rate from homogeneous and heterogeneous reservoir is simulated to test the possibility of obtaining information about the reservoir by temperature.

Simulation parameters: well radius 0.1 m; damage radius near wellbore zone 0.5 m; reservoir radius 10 m; wellhead flow rate 100 m^3/day for 10 hours and 50 m^3/day at a later time; the initial pressure in the well and reservoir 200 atm; initial temperature in the reservoir 20°C; permeability of damage zone 50 md, permeability of reservoir 100 md; porosity 0.2; thickness 5 m; viscosity of the fluid 1 cPs; Joule-Thomson coefficient 0.02 K/atm; Adiabatic coefficient 0.003 K/atm; rock heat capacity 800 J/(kg·K); water heat capacity 4150 J/(kg·K); rock density 2200 kg/m^3; water density 1000 kg/m^3.

Figure 4 shows that the temperature decreases after reduction of flow rate. In the case of heterogeneous reservoir the temperature change is greater as the magnitude of draw-down pressure due to a decrease permeability in the near-wellbore zone more than for a homogeneous reservoir. The following algorithm (based on solution (31)) is used to define the boundaries of damage zone:

1. Draw the chart:

$$\left|T(r,t)\big|_{t>tp} - T(r,t_p)\right| \text{ and } \ln(t-t_p)$$

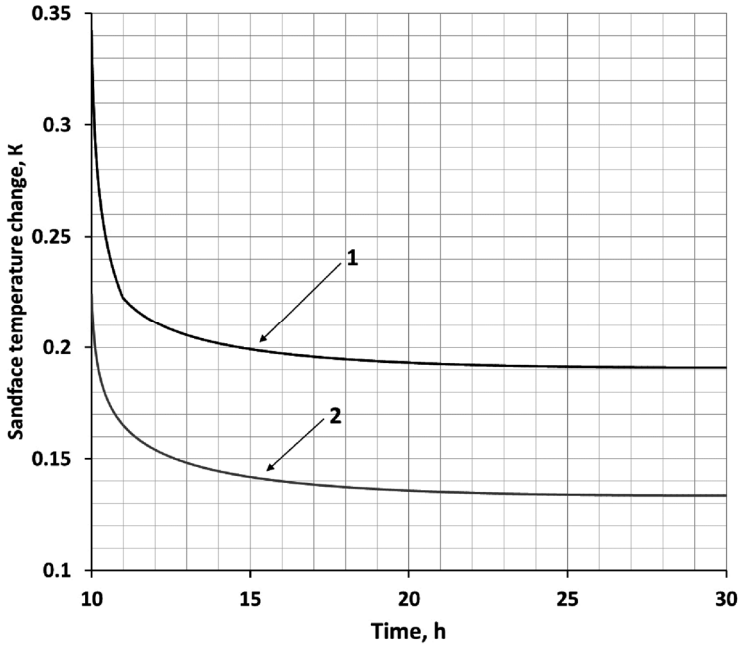

Figure 4 – Sandface temperature change after change flow rate
(1 – heterogeneous reservoir, 2 – homogeneous reservoir)

2. Select the straight sections on the chart
3. Find time, which corresponds to a break in the chart
4. According to the formula (32) calculate the damage radius of near wellbore zone. T^* – temperature at the time of changing flow rate, $T^* = T(t_p)$.

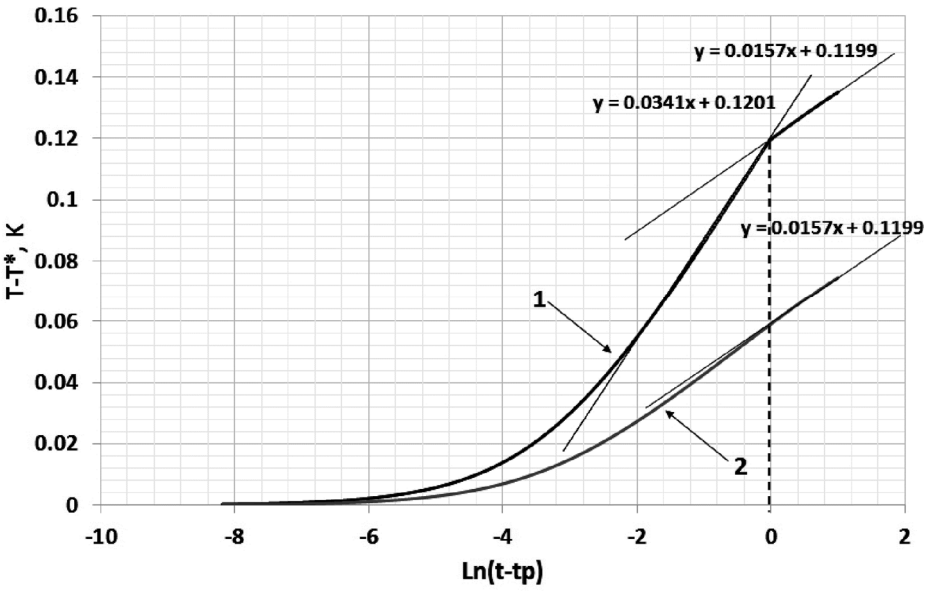

Figure 5 – Sanface temperature change after change flow rate
(1 – heterogeneous reservoir, 2 – homogeneous reservoir)

Time after changing flow rate corresponding to the point of break is 0.96 hours (Δt_p), and the damage radius of near wellbore zone 0.497 meters. The difference between the specified damage radius and the resulting inverse problem solution is 0.48 %.

One more proof that the unsteady temperature from inflowing fluid after changing flow rate brings information about a damage radius zone is illustrated on Figure 6. As an example of three model curves shows the slope of the curves in a semi-logarithmic coordinates after the break the same and equal to 0.0229 K. This is explain by the same permeability's distant zones – 100 md.

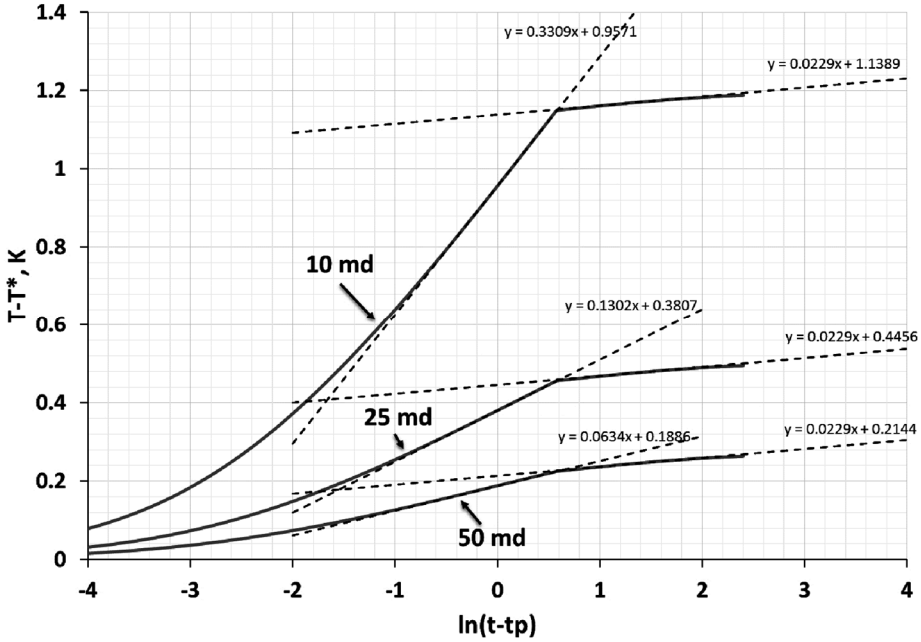

Figure 6 – Sandface temperature change after changing flow rate (permeability of near wellbore zone 10 md, 25 md, 50 md)

Conclusions

1. Analytical model is developed to describe the non-stationary temperature field during a single-phase fluid filtration in the reservoir with the radial inhomogeneity after changing of flow rate. It is based upon convective heat transfer and barothermal effect.

2. Comparison calculations of analytical model with the numerical solution that takes into account thermal conductivity and compressibility showed that the influence of the thermal conductivity and compressibility on the simulation results is negligible.

3. As a result of model research it is clear that damage radius of near wellbore can be estimated by the curves of temperature history recorded after flow rate change.

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