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INFLUENCE OF TEMPERATURE OF WATER TO OIL DISPLACEMENT

1. INTRODUCTION

Laws of heat transport in formations as heterogeneous are similar to laws of salts exchange because the processes have got identical physical basis. First of all both processes are limited by pore mass and heat diffusion, in other word its occur in pore-diffusion kinetic region. While pore dimension of real formation structures are within some parts of micron, so one may account velocity as infinitely quick.

2. DESCRIPTION OF MODEL

We shall consider movement of not mixing up liquids in view of processes of heat exchange on the basis of mathematical Buckley-Leverett model of immiscible fluids transport, being limited to a case one-dimensional movements [1]:

$$v_i = -\frac{k}{\mu_i} f_i(s) \frac{\partial p}{\partial x} \quad (1a)$$

$$m \frac{\partial s}{\partial t} + \frac{\partial v}{\partial x} = 0 \quad (1b)$$

$$-m \frac{\partial s}{\partial t} + \frac{\partial v_1}{\partial x} = 0 \quad (1c)$$

Supposes, as is known, the first integral

$$v + v_1 = V(t) \quad (2)$$

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Also has the common decision of a kind

$$X(s, \tau) = \tau F'(s) + X^0(s) \quad (3)$$

where:

$$\begin{aligned} s & - \text{saturation of oil,} \\ X^0(s) & - \text{distribution of an initial saturation,} \\ \tau & = \frac{1}{m_0} \int_0^t V(t) dt, \\ X & - \text{the transformed independent variables,} \\ F'(s) & - \text{derivative from functions of Leverett.} \end{aligned}$$

At not mixing up filtration change of temperature influences basically factor $\alpha = \mu_1/\mu$, where μ , μ_1 – viscosity of oil and water accordingly. Characteristics of biphasic current are directly defined by properties of function of Leverett $F(s, \alpha(T))$ and its derivative on a saturation $F'(s, \alpha(T))$. If an interval of change of a saturation $(0, s_0)$ where s_0 – the initial saturation in a layer, comprises a point of a maximum of function $F'(s, \alpha(T))$ the decision (3) will undergo break. In this case saturations at the front break s_f in view of a kinematical condition on mobile front

$$m(s_0 - s_f) \frac{dx_f}{dt} = v_1(x_f - 0, t) - v_1(x_f + 0, t) \quad (4)$$

Leads to the transcendental equation on size s_f of a kind

$$s_f(\alpha(T)) = \frac{s_0 - [F(s_0, \alpha(t)) - F(s_f, \alpha(t))]}{F'(s_f, \alpha(T))} \quad (5)$$

and for average on area of replacement of a saturation the formula of a kind turns out

$$\langle s(\alpha) \rangle = \frac{1}{x_f} \int_0^{x_f} s(x, t) dx = s_f - \frac{F(s_f)}{F'(s_f)} \quad (6)$$

Apparently, all these characteristics because of change viscosity of fluids seems dependent on temperature of water getting into a layer. Including the layer saturated by fluids heterogeneous structure, heat exchange between elements of this structure we shall present the equation of kinetic a kind

$$\alpha_T \frac{\partial T_p}{\partial t} = T_0 - T_p \quad (7)$$

where:

$$\begin{aligned} \alpha_t & - \text{kinetics small parameter,} \\ T_p & - \text{temperature of a skeleton of the porous environment and, probably, together} \\ & \text{with the motionless liquids connected with its temperature in mobile fluids.} \end{aligned}$$

Heat transports, carried out by these fluids (water and oil) it is described by the equation of hyperbolic type

$$(v_1 c_1 \rho_1 + v c \rho) \frac{\partial T_0}{\partial x} + m(c_1 s_1 \rho_1 + c s \rho) \frac{\partial T_0}{\partial t} + (1-m)c_p \rho_c \frac{\partial T_p}{\partial t} = 0 \quad (8)$$

where: c, c_1, c_c – specific thermal capacities of oil, water and a skeleton of environment accordingly.

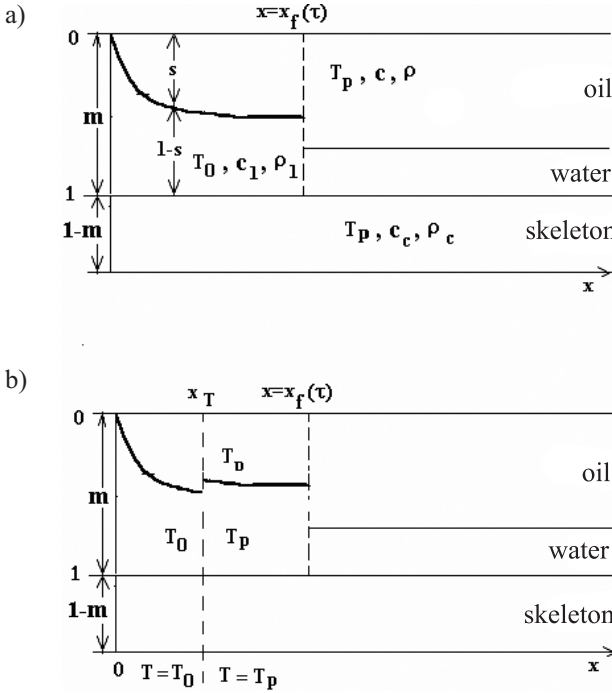


Fig. 1. Conditions of heterogeneous system

In Figure 1 two conditions of heterogeneous system of an oil layer are presented at penetration into it of water with the set temperature T_0 . In condition I (Fig. 1a) thermal interaction is absent. The general Q this condition in a zone of penetration is size

$$Q = (1-m)c_c \rho_c T_p x_f(t) + m c \rho T_p \int_0^{x_f} s dx + m c_1 \rho_1 T_0 \int_0^{x_f} (1-s) dx \quad (9)$$

For a condition II (Fig. 1b) reflecting an instant establishment of thermal balance in times of a layer (α_T in the equation of kinetic infinitesimal) presence mobile of adiabatic border $x = x_T(\tau)$, limiting thermal influence on a layer is characteristic.

$$\begin{aligned}
Q = & (1-m)c_c \rho_c T_0 x_T(t) + mc\rho T_0 \int_0^{x_T} s dx + mc_1 \rho_1 T_0 \int_0^{x_T} (1-s) dx + \\
& + (1-m)(x_f - x_T)c_c \rho_c T_p + mc\rho T_p \int_{x_T}^{x_f} s dx + mc_1 \rho_1 T_p \int_{x_T}^{x_f} (1-s) dx
\end{aligned} \tag{10}$$

Comparing the right parts of the equations (9) and (10), in view of break of saturations on thermal front $x = x_T$, we shall receive the equation of balance of thermal energy for definition of depth x_T of cooling $T_0 < T_p$ or a warming up (in case of an opposite inequality) in near well-boring areas of a layer.

$$\begin{aligned}
& (1-m)c_c \rho_c x_f + mc\rho \int_0^{x_T} s^- dx + mc\rho \int_{x_T}^{x_f} s^+ dx + mc_1 \rho_1 \lambda_T [x_f - \int_0^{x_T} s^- dx - \int_{x_T}^{x_f} s^+ dx] = \\
& = (1-m)c_c \rho_c \lambda_T x_T + mc\rho \lambda_T \int_0^{x_T} s^- dx + mc_1 \rho_1 \lambda_T [x_T - \int_0^{x_T} s^- dx] + \\
& + (1-m)(x_f - x_T)c_c \rho_c + mc\rho \int_{x_T}^{x_f} s^+ dx + mc_1 \rho_1 [x_f - x_T - \int_{x_T}^{x_f} s^+ dx]
\end{aligned}$$

Entering dimensionless parameters:

$$\lambda_T = \frac{T_0}{T_p},$$

$$\lambda_m = \frac{1-m}{m},$$

$$\lambda_c = \frac{c}{c_1},$$

$$\lambda_{cc} = \frac{c_c}{c_1},$$

$$\lambda_p = \frac{\rho}{\rho_1},$$

$$\lambda_{pc} = \frac{\rho_c}{\rho_1}.$$

The equation of balance of quantity of heat received above will be transformed to a kind

$$\begin{aligned}
x_T (\lambda_m \lambda_{cc} \lambda_{pc} + 1) = & x_f - \lambda_c \lambda_p \tau [s_T^- F'_-(s_T^-) - F_-(s_T^-)] - \\
& - \tau [s_f F'_+(s_f) - s_T^+ F'_+(s_T^+) - F_+(s_f) + F_+(s_T^+)]
\end{aligned} \tag{11}$$

Equation (11) defines border cooled (or warming up) parts of a layer and such, that at

$$x < x_T, s = s^-,$$

and at

$$x < x_T,$$

accordingly

$$s = s^+.$$

According to known property of functions of Leverett:

$$v^\pm = V(t)F_\pm(s^\pm, \alpha^\pm),$$

$$v_1^\pm = V(t)(1 - F_\pm(s^\pm, \alpha^\pm)).$$

It is obvious, that on border of thermal front the continuity of speeds of a filtration of oil and water will provide a condition

$$F_+(s_T^+, \alpha^+) = F_-(s_T^-, \alpha^-),$$

or in the developed kind

$$\frac{\alpha^+ f(s_T^+)}{\alpha^+ f(s_T^+) + f_1(s_T^+)} = \frac{\alpha^- f(s_T^-)}{\alpha^- f(s_T^-) + f_1(s_T^-)} \quad (12)$$

Besides from representation of the decision (3) we also have one more parity

$$x_T = X_T^- = \tau F'_-(s_T^-) \quad (13)$$

As it is told above, the saturation sf at the front replacement

$$x = x_f = \tau F'_+(s_f),$$

will be defined from a kinematical condition which will lead to the transcendental equation (5). In this case it looks like

$$s_f = s_0 - \frac{[F_+(s_0, \alpha^+) - F_+(s_f, \alpha^+)]}{F'_+(s_f, \alpha^+)} \quad (14)$$

3. ALGORITHM

Thus, the algorithm of construction of the decision is reduced to the following. The initial saturation of a layer, value of density, specific thermal capacities of all phases, tem-

perature of a layer and temperature of begun to the swing waters are set. Under tables are viscosity of fluids at two set T_0 , T_p and sizes α^\pm are calculated. The equation (14) further is solved. For the remained three unknown persons s_T^\pm , x_T it is necessary to solve system of three nonlinear equations (11)–(13). All parameters of current and distribution of phases will be found by that from representation of decisions (3) in corresponding areas.

According to the described algorithm at:

$$T_p = 80^\circ\text{C},$$

$$T_0 = 20^\circ\text{C},$$

$$\alpha^+ = 0.33,$$

$$\alpha^- = 0.1,$$

results of calculations are presented in Figure 2.

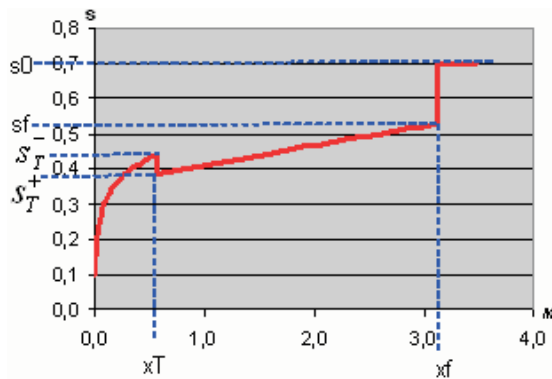


Fig. 2. Distribution of saturation at $T_0 < T_p$

For a case of forcing of the hot heat-carrier in a layer at values:

$$T_p = 20^\circ\text{C},$$

$$T_0 = 80^\circ\text{C},$$

$$\alpha^+ = 0.1,$$

$$\alpha^- = 0.33,$$

$$\tau = 1.5.$$

results of calculations are presented in Figure 3. Without taking into account thermal processes at the same values results are presented in Figure 4.

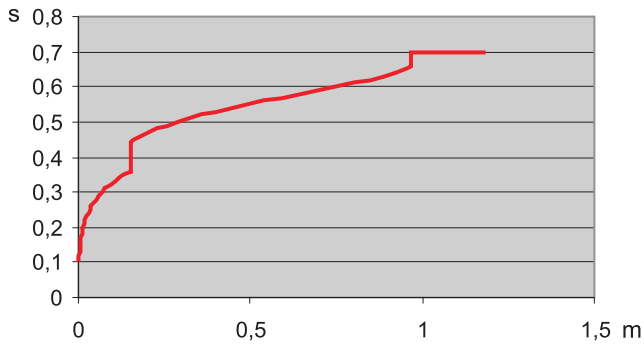


Fig. 3. Distribution of saturation at $T_0 > T_p$

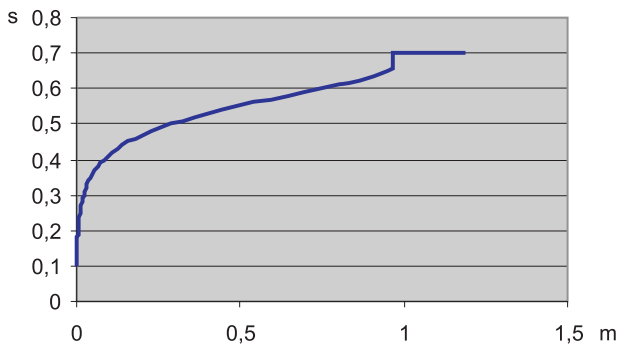


Fig. 4. Distribution of without taking into account thermal interaction

Numerical experiments show, that temperature the front lags behind front of a saturation and the case of warming up of an oil layer

$$T_0 > T_p,$$

increases only a degree of final petrofeedback. At calculations it is shown in the form of occurrence of additional front of replacement (area of greater gradients of a saturation), corresponding thermal front (area of greater gradients of temperature). Thus, non-isothermal process of a filtration (heating or cooling of a water phase) allows to operate structure of distribution of a saturation of considered area and its value effectively is numerically.

Analogical results turn out and for the radially-symmetric case of motion of liquids in a porous environment.

For evident ness will make an example character of distributing of specific electric resistance depending on a temperature penetrable in the layer of boring solution for the radially-symmetric case, which calculated on the basis of law of Archie in generalized form [2, 3]

$$R_{s_1} = s_1^{-n} a \frac{0.0123 + 3647.5C^{-1}}{1.8T + 39},$$

where:

- R_{s_1} – specific electric resistance of breed with the saturation s_1 of pores water and concentration;
- T – temperature [$^{\circ}\text{C}$];
- n – index, equal approximately 2;
- a – some permanent for this type of breed.

In accordance with the generalized law of Archie, resistance of area of penetration R_{nT} , frappe a filtrate, is related to ordinary “attachment” R_n correlation with

$$R_{nT} = \frac{1.8T_p + 39}{1.8T_0 + 39} R_n,$$

i.e. utilizing the indicated formula, for example, at

$$T_p = 80^{\circ}\text{C},$$

and

$$T_0 = 20^{\circ}\text{C},$$

will get

$$R_{nT} = 2.4 R_n.$$

Distribution of veritable specific electric resistance in near well-boring areas under of law of Archie looks like:

$$R = \begin{cases} R_{nT} = R_n (1.8T_p + 39) / (1.8T_0 + 39), & 0 < r < r_T \\ R_n = R_n^0 / (1 - \langle s \rangle)^2, & r_T < r \leq r_{oz} \\ R_{oz} = R_0^0 / (1 - \langle s \rangle)^2, & r_{oz} < r < r_f \\ R_0 = R_0^0 / (1 - s_0)^2, & r_f < r \end{cases}$$

where:

- R_0^0 – specific electric resistance in near well-boring areas completely saturated by a filtrate,
- R_n^0 – specific electric resistance in not indignant part of a layer.

4. RESULTS

Results of calculations of veritable specific electric resistance of layer for a temperature model are presented in Figure 5.

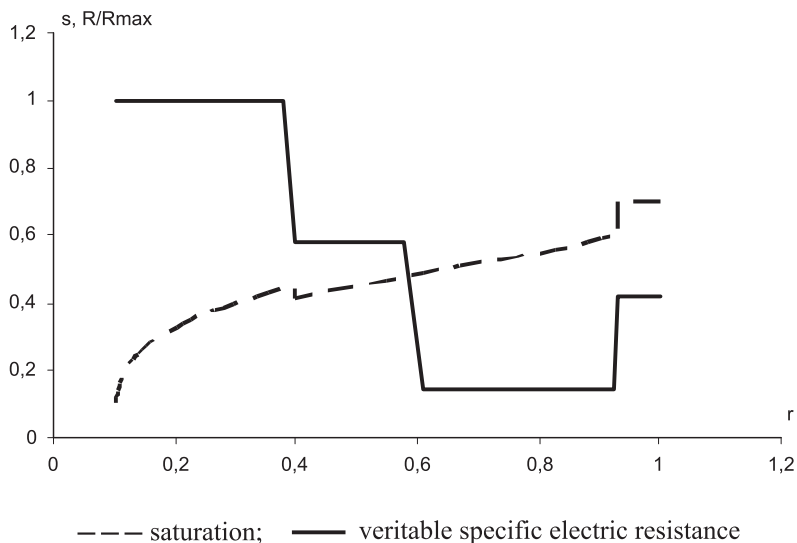


Fig. 5. Distribution of s and of veritable specific electric resistance

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