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Hydrodynamics Problems for Distribution of the Phases in Oil-and-Gas Formation

V.I. PEN'KOVSKII, N.K. KORSAKOVA
Lavrentyev Institute of Hydrodynamics SB RAS,
630090, Lavrentjev pr. 15, Novosibirsk
RUSSIA
penkov@hydro.nsc.ru, kors@hydro.nsc.ru

Developed method of oil and gas formation electromagnetic logging is based on representation of apparent resistivity as convolution of real resistivity field with frequency distribution for every sonde sensitivity on near-well zone, mathematical modeling of drilling mud filtrate penetration processes and interaction of mud filtrate with native water.

Hydrodynamics of drilling mud filtrate invasion into formation is defined by solution of Buckley-Leverett system of equations with observance of kinematic conditions for phase discontinuity. As result the displacement front locations and oil and gas mean-integral values of the saturations in drilling mud filtrate invasion region are obtained. Depending on formation saturations of immiscible phases different cases of mutual displacement oil, gas and water front locations are possible. The location of fronts affects essentially to character of resistivity distribution and logging reading. The interpretation of field data is reduced to solution of inverse problems so as definition of initial data for system of immiscible liquid and salt-exchange equations. The example of applying of the method is given.

1 Focusing properties of sounders

Archie law is connecting-link between sonde data of High Frequency Inductive Isoparametric Logging (HFIIL) tool and resistivity of near-well zone $R = R(r,z)$ (r, z are radial and vertical coordinates). As follows from the law formation resistivity is inversely to squared electrolyte saturation of stratum pore space when other conditions are equal. So called apparent resistivity is calculated with use of phase difference of electrical signals which come to exploring coil. Value of the resistivity is some average electrophysical characteristic of stratum volume bounded by two synphase surfaces that traverse generating and two exploring coils. Apparent resistivity $\overline{R(r)}$ coincides with real resistivity in case of electrically uniform media only. Generally measured by every sonde i apparent resistivity can be presented as probabilistic convolution [1]

$$\overline{R_i} = \int_0^\infty R(r)\frac{1}{2\sqrt{2\pi}\sigma x_{ci}}\exp(-\sigma^2)\exp(-\frac{1}{2\sigma^2}\ln^2\frac{x}{x_{ci}})dr \quad (1)$$

Here $x = r^2$, $x_{ci} = r_{ci}^2$ are squares of sensitivity centres, $\sigma = 0.68$-0.7 is dispersion as parameter which characterizes constructional property of tool.

For HFIIL tool conditions $\Delta L_i / L_i = 0{,}2$ and $\sqrt{f_i}L_i = \text{const}$ are observed, where L_i is length of sonde, ΔL_i is base, the distance between the measuring coils, f_i is the radiation frequency of the generative coils [2]. We will prove that sensitivity centres r_i are located at distance equal semilengths of sondes from hole axis.

Simulated generating coils electrical dipoles are shown schematically on plain (fig. 1). The coils are located in point of origin. Let consider the first quadrant of the plain.

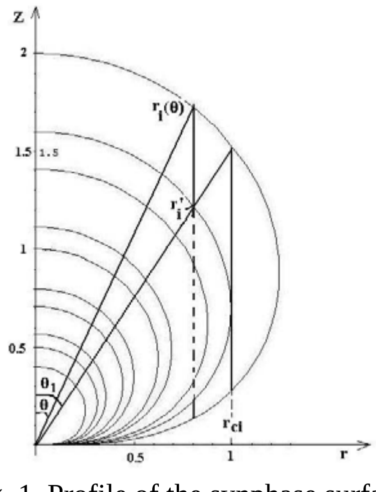

Fig. 1. Profile of the synphase surfaces.

For uniform media dipole potential ϕ with axis z is

$$\phi = \frac{(M\vec{k}_0 * \vec{r})}{r^3} = \frac{M|\vec{k}_0||\vec{r}|\cos\theta}{r^3} = \frac{M\cos\theta}{r^2} .$$

Here $\theta \in (0, \pi/2)$ is angle between radius-vector $\vec{r}$ and axis z with unit ort $\vec{k}_0$, M is dipole moment. Thus, intersection of synphase surface of dipole with vertical plain on polar coordinates can be presented

$$r = r_i(\theta) = L_i\sqrt{\cos\theta} \ \ (L_i = \sqrt{M/\phi_i}) . \qquad (2)$$

Sounding stratum volume is presented as around axis z rotation figure of area closed between curve (2) and coupled curve defined by

$$r = r_i'(\theta_1) = L_i'\sqrt{\cos\theta_1} . \qquad (3)$$

θ_1 is angle coordinate of point r_i'. Both the point and point r_i belong to the same vertical line. For HFIIL tool it is $L_i' = 0.8L_i$.

Maximal increase of stratum volume is achieved near vertical tangent to curve $r = r_i'$. Let x_i, z_i and x_i', z_i' are accordingly Cartesian coordinates of points in formulas (2) and (3). They are presented by expressions

$$x_i = r_i\sin\theta = L_i\sin\theta\sqrt{\cos\theta} = x_i' =$$
$$= L_i'\sin\theta_1\sqrt{\cos\theta_1} ;$$
$$z_i = r_i\cos\theta = L_i(\cos\theta)^{3/2};$$
$$z_i' = L_i'(\cos\theta_1)^{3/2} .$$

Denoting $\alpha_1 = \cos\theta_1 \in (0,1)$, for x_i' we obtain formula $x_i' = L_i\sqrt{\alpha_1(1-\alpha_1^2)}$. Passed over some point of curve $r = r_i$ vertical line is tangent to curve $r = r_i'$ when $\frac{dx_i'}{d\alpha_1} = 0.$ Results from this that maximum $x_i' = x_{ci}$ is at the high when $\alpha_1 = \alpha_c = 1/\sqrt{3}$ and $x_{ci} = 0.6204L_i' = 0.4963L_i \approx 0.5L_i$, which required.

2 Mathematical modeling of invasion process of mud filtrate into stratum

The process of immiscible filtration is described within the framework of the Buckley-Leverett scheme by mass conservation laws

$$\frac{1}{r}\frac{\partial}{\partial r}(rv_i) + m\frac{\partial s_i}{\partial t} = 0, \quad (i = ,0,1) \qquad (4)$$

here indexes 1 denotes water, 0 is gas, without index indicates oil, and equations of motion as generalized Darcy law

$$v_i = -k_i f_i \frac{\partial h}{\partial r}$$

and algebraic relations

$$\sum_i s_i = 1 . \qquad (5)$$

Here $k_i = k/\mu_i$, $f_i \approx s_i^n$ $(n \approx 3.5)$ are relative phase permeabilities.

Summarizing all equations from (4) and using relation (5) one obtains the first integral

$$r(v + v_0 + v_1) = r_w V(t) . \qquad (6)$$

Velocities of phases are presented as

$$rv_i = F_i(s, s_0) r_w V(t) ,$$

$$F_i(s, s_0) = \frac{\alpha_i f_i(s_i)}{\sum_i \alpha_i f_i (s_i)}$$ are generalized Leverett's functions. The functions satisfy relations

$$\sum_i F_i(s, s_0) = 1,$$

$(\alpha_i = \mu_i/\mu_1, \alpha_1 = 1, \quad \alpha \le 1 , \quad \alpha_0 >> 1).$

Introducing new independent variables

$$\tau = \frac{2}{mr_w}\int_0^t V(r_w, t)dt; \quad x = (\frac{r}{r_w})^2,$$

equations (4) are reduced to view like equations of one-dimensional motion

$$\frac{\partial s_i}{\partial \tau} + \frac{\partial}{\partial x}(F_i) = 0 .$$

In the presence of the first integral (6) from three equations above suffice it to reserve two only

$$\begin{aligned} &\frac{\partial s}{\partial \tau} + \frac{\partial F}{\partial s}\frac{\partial s}{\partial x} + \frac{\partial F}{\partial s_0}\frac{\partial s_0}{\partial x} = 0 \\ &\frac{\partial s_0}{\partial \tau} + \frac{\partial F_0}{\partial s}\frac{\partial s}{\partial x} + \frac{\partial F_0}{\partial s_0}\frac{\partial s_0}{\partial x} = 0 \end{aligned} . \qquad (7)$$

Let $s^0, s_1^0, s_0^0 = 1-(s^0 + s_1^0)$ are initial saturations of formation by oil, water and gas, accordingly. The mobility of every phase depends on its partial saturation and viscosity. In general it defined by products $\alpha_i f_i$. Let r_{f0} and r_f are radii of displacement fronts of gas and oil by water phase. As gas phase is the most mobile ($\alpha_0 \approx 50$) when other conditions are equal so gas displacement is faster then not great oil one in stratum. At the same time displacement front of gas passes ahead of oil displacement front $r_{f0} > r_f$. At phase displacement fronts kinematic conditions should be hold as

$$\begin{aligned} &v_i(r_{fi} - 0, t) - v_i(r_{fi} + 0, t) = \\ &m[s_i(r_{fi} - 0) - s_i(r_{fi} + 0)]\frac{dr_{fi}}{dt} \end{aligned} . \qquad (8)$$

It is well known that functions $s(r,\tau)$ and $s_0(r,\tau)$ discontinue on oil and gas fronts of displacement. When process of gas displacement passes ahead of oil frontal advance the values of saturations s_{0f} and s_f on displacement fronts could be found from solutions of the transcendental equations

$$s_{0f} = s_0^0 - (F_0(s^0, s_0^0) - F_0(s^0, s_{0f}))/\frac{\partial F_0(s^0, s_{0f})}{\partial s_0}, \quad (9)$$

$$s_f = s^0 - (F(s^0, <s_0>) - F(s_f, <s_0>))/\frac{\partial F(s_f, <s_0>)}{\partial s}. \quad (10)$$

Those equations are consequence from kinematic conditions (8).

Using solution of system of equations (7) and taking into account dependence between variable τ and radius of volume mud filtrate invasion $r_n = r_w\sqrt{1+\tau}$ we obtain expressions for radii of displacement fronts of gas and oil phases

$$r_{f0} = \sqrt{r_w^2 + (r_n^2 - r_w^2)\frac{\partial F_0(s^0, s_{0f})}{\partial s_0}},$$

$$r_f = \sqrt{r_w^2 + (r_n^2 - r_w^2)\frac{\partial F(s_f, <s_0>)}{\partial s}}.$$

It can be proved that mean-integral values of the gas and oil saturations is calculated by formulas

$$<s_0> = s_{0f} - F_0(s^0, s_{0f})/\frac{\partial F_0(s^0, s_{0f})}{\partial s_0}, \quad (11)$$

$$<s> = s_f - F(s_f, <s_0>)/\frac{\partial F(s_f, <s_0>)}{\partial s}. \quad (12)$$

Those mean-that integral values do not depend on time of displacement.

In calculations Leverett's functions are taken as

$$F_0(s, s_0) = \frac{\alpha_0 s_0^{3,5}}{\alpha s^{3,5} + \alpha_0 s_0^{3,5} + (1 - s - s_0)^{3,5}},$$

$$F(s, s_0) = \frac{\alpha s^{3,5}}{\alpha s^{3,5} + \alpha_0 s_0^{3,5} + (1 - s - s_0)^{3,5}}.$$

3 Interaction of water solutions Resistivity of invasion zone

Saturated by three immiscible phases such as oil, gas and native water, stratum is heterogeneous medium. When mud filtrate penetrates into near well zone, salt exchange between water phases takes place for pore-diffusion kinetic. Thus the process of phase interfusion can be accounted as instantaneous.

System of equations for interaction of water solutions on heterogeneous formation consists of mass transport equation and salt exchange kinetic equation

$$\begin{cases} \frac{1}{r}\frac{\partial}{\partial r}[rv_1(r,t)C] + \frac{\partial}{\partial t}[m(s_1(r,t) - s_1^0)C] + \frac{\partial}{\partial t}(ms_1^0 N) = 0, \quad (13) \\ \alpha_c \frac{\partial N}{\partial t} = C - N, \end{cases}$$

where C is salt concentration of penetrating solution, N is salt concentration of native water, s_1 is water saturation, s_1^0 is initial water saturation of formation.

Velocity of water motion is $v_i = F_i(s, s_0) r_w V(t)/r$. Taking into account conservation law of water phase volume system (13) is transformed to equations

$$\begin{cases} F_1(s, s_0)\frac{\partial C}{\partial x} + (s_1(x,\tau) - s_1^0)\frac{\partial C}{\partial \tau} + s_1^0 \frac{\partial N}{\partial \tau} = 0. \quad (14) \\ \frac{2}{mr_w} V(\tau)\alpha_c \frac{\partial N}{\partial \tau} = C - N \end{cases}$$

In general case for system (14) the boundary conditions of Gursa problem are laid down as data on characteristics

$$x = 1: \ C = C_p; \qquad \xi = \xi_2(\tau): N = C_0.$$

Here C_p is salt concentration of water on input of formation, C_0 is unchanged salt concentration of native water. Characteristic ξ_2 is defined from equation

$$\frac{d\xi_2}{F_1(s, s_0)} = \frac{d\tau}{s_1(\xi, \tau) - s_1^0}$$

using condition $\xi_2(0) = 1$.

Mass salt exchange occurs within pore-diffusion field of kinetic and real size of pores is very small. So one might consider $\alpha_c \approx 0$. In that case the system (10) degenerates to only convective transport equation

$$F_1(s,s_0)\frac{\partial C}{\partial x}+s_1(x,\tau)\frac{\partial C}{\partial \tau}=0 \ .$$

Solution of the equation is first member of asymptotic expansion for solution of total system in series for small parameter α_c.

Characteristic of singular equation $\xi=\xi_1$ is defined by differential equation

$$\frac{d\xi_1}{F_1(s,s_0)}=\frac{d\tau}{s_1(\xi,\tau)} \qquad (\xi_1(0)=1).$$

Apparently $\xi_1<\xi_2$ (fig. 2), and approximate solution is presented as

$$C=N=\begin{cases}C_p\ , & 1\le\xi<\xi_1(\tau)\\ C_0\ , & \xi_1(\tau)\le\xi<\xi_2(\tau)\end{cases}$$

$$N\equiv C_0 \ \text{for} \ \xi>\xi_2 .$$

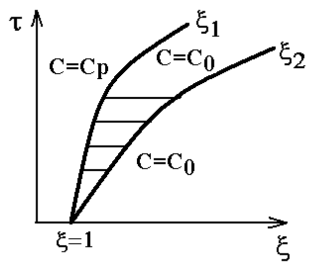

Fig. 2. Field of solution.

Let $r_{f1}=r_w\sqrt{\xi_1}$ is boundary separated fresh mud filtrate $C=C_p$ from solution of native water $C=C_0$ saturated by salt. Using known values of radius of displacement fronts r_f and r_{f0} bounds of mixture zone of the solutions can be obtained using proper balance relation [3].

The location of displacement fronts of every phase is defined by their saturation and viscosity. On fig. 3 it is shown the dependence of positions for radius r_{f1} and displacement front of oil from formation saturation by oil. As the best obviousness the example is demonstrated for only oil and water case. The dimensionless relation of oil and water viscosities α is accepted 0.33, well radius r_w is equal to 0.108 m. When oil saturation vanished the radius of displacement front of salt water r_{f1} works for radius of volume mud filtrate invasion and there is a case of displacement of salt water by fresh mud filtrate. At that time radius of oil front displacement r_f works to r_w. The radii r_f and r_{f1} intersect at point corresponding to value of oil saturation equals to 0.44. When oil saturation in formation is greater then this value there is low resistivity zone. Presence of that zone serves to definition of oil availability in reservoir. For α =0.44 the width of low resistivity zone between r_f and r_{f1} amounts to maximum one when $s^0\approx 0.6$.

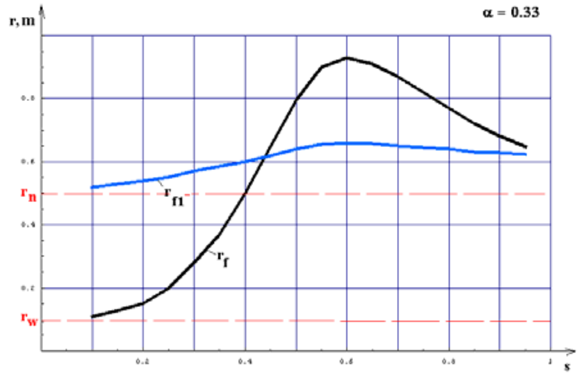

Fig. 3. The location of displacement front of oil and radius of low-resistivity zone.

Six cases of location of displacement fronts and bounding zone for three phase flow can be possible

(A) $r_f<r_{f1}<r_{f0}$;

(B) $r_{f1}<r_f<r_{f0}$;

(C) $r_{f0}<r_{f1}<r_f$;

(D) $r_{f0}<r_f<r_{f1}$;

(E) $r_f<r_{f0}<r_{f1}$;

(F) $r_{f1}<r_{f0}<r_f$.

In case (A) mass balance of solute salt in mud filtrate leads to relations

$$(r_f^2-r_w^2)(1-\langle s\rangle-\langle s_0\rangle)+ (r_{f1}^2-r_f^2)(1-s^0-\langle s_0\rangle)=r_w^2\tau \ ,$$

$$r_w^2\tau=(r_{f0}^2-r_w^2)/\frac{\partial F_0(s^0,s_{f0})}{\partial s_0}= =(r_f^2-r_w^2)/\frac{\partial F(s_{f,}\langle s_0\rangle)}{\partial s} \ .$$

From balance equations for radius of cylindrical surface r_{f1} separating part of formation occupied by mud filtrate from part saturated by native water, we obtain formula

$$r_{f1}^2 - r_w^2 = \frac{r_{f0}^2 - r_w^2}{(1 - s^0 - \langle s_0 \rangle)\dfrac{\partial F_0(s^0, s_{f0})}{\partial s_0}} \cdot$$

$$\cdot \left[1 - (s^0 - \langle s \rangle) \frac{\partial F(s_f, \langle s_0 \rangle)}{\partial s} \right]$$

Thus, according to Archie law for case (A) distribution of real resistivity can be presented as piecewise function including four steps.

$$R = \begin{cases} R_n = R_n^0 /(1 - \langle s_0 \rangle - \langle s \rangle)^2, & r_c \le r < r_f \\ R_{oz1} = R_n^0 /(1 - \langle s_0 \rangle - s^0)^2, & r_f < r < r_{f1} \\ R_{0z2} = R_0^0 /(1 - \langle s_0 \rangle - s^0)^2, & r_{f1} < r < r \\ R_0 = R_0^0 /(1 - s_0^0 - s^0)^2, & r_{f0} < r < \infty. \end{cases}$$

Here R_0^0 is resistivity of saturated by native water formation and R_n^0 is resistivity of saturated formation by mud filtrate.

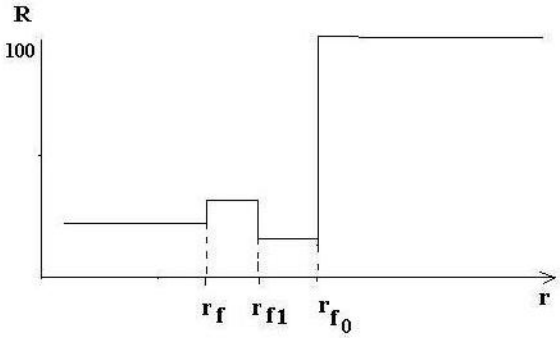

Fig. 4. The real resistivity (case A).

There is a modeling example of resistivity distribution on fig. 4. The stepped graphic is shown for specified parameters such as initial oil saturation s^0=0.3, initial gas saturation s_0^0=0.6, radius of volume mud filtrate invasion r_n =0.5 m, resistivity R_0^0=1 Om·m, resistivity R_n^0=4 Om·m. The complicated distribution includes not only well known low-resistivity zone but heightened resistivity zone between radius of displacement oil front r_f and boundary of water solutions r_{f1}.

Theoretically the apparent resistivity of stratum is presented as integral probabilistic convolution of real resistivity using (1)

$$\bar{R}(r) = \frac{R_n - R_{oz1}}{2}\left[1 + erf\left(\frac{1}{2\sqrt{\sigma}} \ln \frac{x_f}{x} - \frac{\sigma}{\sqrt{2}}\right)\right] +$$

$$+ \frac{R_{oz1} - R_{oz2}}{2}\left[1 + erf\left(\frac{1}{2\sqrt{\sigma}} \ln \frac{x_{f1}}{x} - \frac{\sigma}{\sqrt{2}}\right)\right] +$$

$$+ \frac{R_{oz2} - R_0}{2}\left[1 + erf\left(\frac{1}{2\sqrt{\sigma}} \ln \frac{x_{f0}}{x} - \frac{\sigma}{\sqrt{2}}\right)\right] + R_0 .$$

When radii of phase fronts are located as $r_{f1} < r_f < r_{f0}$ (case (B)) the situation is according to low content of water phase in stratum. In that case from corresponding balance relation we obtain

$$r_{f1}^2 - r_w^2 =$$

$$= (r_f^2 - r_w^2) / \left[(1 - \langle s \rangle - \langle s_0 \rangle) \frac{\partial F(s_f, \langle s_0 \rangle)}{\partial s} \right].$$

The real resistivity function is given by

$$R = \begin{cases} R_n = R_n^0 /(1 - \langle s_0 \rangle - \langle s \rangle)^2, r_c \le r < r_{f1} \\ R_{oz1} = R_0^0 /(1 - \langle s_0 \rangle - \langle s \rangle)^2, r_{f1} < r < r_f \\ R_{0z2} = R_0^0 /(1 - \langle s_0 \rangle - s^0)^2, r_f < r < r_{f0} \\ R_0 = R_0^0 /(1 - s_0^0 - s^0)^2, r_{f0} < r < \infty. \end{cases}$$

The distribution of real resistivity depending from radius is presented on fig. 5 for case (B). The results of calculation were realized for values of initial oil and gas saturation s^0=0.6, s_0^0=0.3.

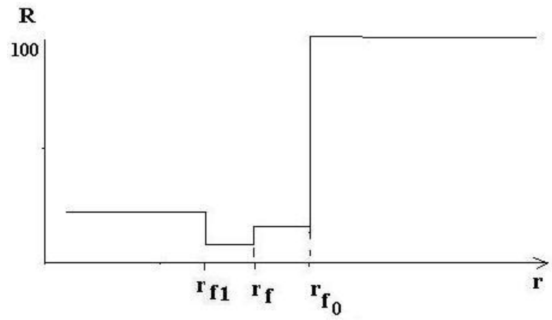

Fig. 5. The real resistivity (case (B)).

The case (C) is corresponding to low gas content of reservoir. Front of gas displacement locates close to wellbore wall because of mobility of gas phase with small saturation becomes commensurable to mobility of liquid phases. Then gas phase is displaced with difficult. In the case (C) displacement oil front

r_f passes ahead of gas displacement. This was described in [1] when one considered model of piston gas displacement for three phase system. According to location of the phases the oil and gas front saturation is obtained from the transcendental equations

$$s_f = s^0 - \frac{F(s^0, s_0^0) - F(s_f, s_0^0)}{\dfrac{\partial F(s_f, s_0^0)}{\partial s}}, \quad (15)$$

$$s_{0f} = s_0^0 - \frac{F_0(\langle s \rangle, s_0^0) - F_0(\langle s \rangle, s_{0f})}{\dfrac{\partial F_0(\langle s \rangle, s_{0f})}{\partial s_0}}. \quad (16)$$

Correspondingly, mean-integral values of the oil and gas saturations is calculated by

$$\langle s \rangle = s_f - \frac{F(s_f, s_0^0)}{\dfrac{\partial F(s_f, s_0^0)}{\partial s}} \quad (17)$$

$$\langle s_0 \rangle = s_{0f} - \frac{F_0(\langle s \rangle, s_{0f})}{\dfrac{\partial F_0(\langle s \rangle, s_{0f})}{\partial s_0}}. \quad (18)$$

Radius of oil displacement front for case (C) is taken as

$$r_f = \sqrt{r_w^2 + (r_n^2 - r_w^2)\frac{\partial F(s_f, s_0^0)}{\partial s}}.$$

At that the boundary between native water and fresh mud filtrate, and radius gas displacement front are calculated using expressions

$$r_{f1}^2 - r_w^2 = \frac{r_f^2 - r_w^2}{(1 - \langle s \rangle - s_0^0)\dfrac{\partial F(s_f, s_0^0)}{\partial s}} \cdot \left[1 - (s_0^0 - \langle s_0 \rangle)\frac{\partial F_0(\langle s \rangle, s_{f0})}{\partial s_0}\right]$$

and

$$r_{f0} = \sqrt{r_w^2 + (r_n^2 - r_w^2)\frac{\partial F_0(\langle s \rangle, s_{0f})}{\partial s_0}}.$$

When oil content of formation is low and gas saturation is slight (cases D and E) the mud filtrate ejects native salt water with more speed passing ahead of fronts of oil and gas displacement. In case (D) the quantity of gas is so negligible that it is almost nondisplaced. Thus front of oil displacement locates between front of gas displacement and salt water displacement boundary. According to that the values of saturation on the fronts of immiscible phases, mean values of oil and gas saturation are found from (15)-(18). Radii of fronts of oil and gas displacement are calculated as in case (C).

Location of native water displacement boundary by fresh mud filtrate solution is given by the next expression

$$r_{f1}^2 - r_w^2 = \frac{r_f^2 - r_w^2}{(1 - s^0 - s_0^0)\dfrac{\partial F(s_f, s_0^0)}{\partial s}} \cdot \left[1 + (\langle s \rangle - s^0)\frac{\partial F(s_f, s_0^0)}{\partial s} - (s_0^0 - \langle s_0 \rangle)\frac{\partial F_0(\langle s \rangle, s_{f0})}{\partial s_0}\right].$$

The distribution of real resistivity for case (D) is

$$R = \begin{cases} R_n = R_n^0 / (1 - \langle s_0 \rangle - \langle s \rangle)^2, r_c \le r < r_{f0} \\ R_{oz1} = R_n^0 / (1 - s_0^0 - \langle s \rangle)^2, r_{f0} < r < r_f \\ R_{0z2} = R_n^0 / (1 - s_0^0 - s^0)^2, r_f < r < r_{f1} \\ R_0 = R_0^0 / (1 - s_0^0 - s^0)^2, r_{f1} < r < \infty. \end{cases}$$

Graphical presentation of this function is shown on fig. 6. The values of initial oil and gas saturation s^0=0.3, s_0^0=0.025 are correct for the case.

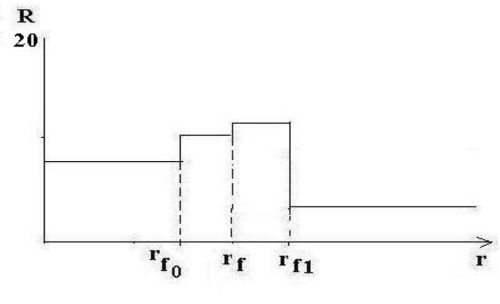

Fig. 5. The real resistivity (case (D)).

In case (E) there are $r_f < r_{f0} < r_{f1}$.

The values of oil and gas saturation on fronts of phase discontinuity, mean values of saturations and radii of oil and gas displacement front are counted like for cases (A) and (B). Other parameters are obtained by the formulas

$$r_{f1}^2 - r_w^2 = \frac{r_f^2 - r_w^2}{(1 - s^0 - s_0^0)\dfrac{\partial F(s_f, <s_0>)}{\partial s}} \cdot$$

$$\cdot \left[1 + (<s> - s^0)\frac{\partial F(s_f, <s_0>)}{\partial s} - \right.$$

$$\left. - (s_0^0 - s_0 >) \frac{\partial F_0(s^0, s_{f0})}{\partial s_0} \right]$$

and

$$R = \begin{cases} R_n = R_n^0 / (1 - s_0 > - s >)^2, r_c \le r < r_{f0} \\ R_{oz1} = R_n^0 / (1 - s^0 - s_0 >)^2, r_{f0} < r < r_f \\ R_{0z2} = R_n^0 / (1 - s_0^0 - s^0)^2, r_f < r < r_{f1} \\ R_0 = R_0^0 / (1 - s_0^0 - s^0)^2, r_{f1} < r < \infty. \end{cases}$$

The situation happens when with high content of oil in formation some quantity of gas phase occurs. At the time front of gas displacement falls on low-resistivity zone before front of oil displacement, in other words there are $r_{f1} < r_{f0} < r_f$ (case (E)). Formulas for calculation of saturation on fronts and locations of the fronts coincide with expressions for cases (C) and (D). Also position of separating surface of mud filtrate penetration and real resistivity get by formulas below

$$r_{f1}^2 - r_w^2 = \frac{r_f^2 - r_w^2}{(1 - <s> - <s_0>)\dfrac{\partial F(s_f, s_0^0)}{\partial s}}$$

and

$$R = \begin{cases} R_n = R_n^0 / (1 - s_0 > - s >)^2, r_c \le r < r_{f1} \\ R_{oz1} = R_0^0 / (1 - s_0 > - s >)^2, r_{f1} < r < r_{f0} \\ R_{0z2} = R_0^0 / (1 - s_0^0 - s >)^2, r_{f0} < r < r_f \\ R_0 = R_0^0 / (1 - s_0^0 - s^0)^2, r_f < r < \infty. \end{cases}$$

The integration of probabilistic convolution gives the expression for the apparent resistivity with account of locations of the fronts

$$\overline{R}(r) = \frac{R_n - R_{oz1}}{2}\left[1 + erf\left(\frac{1}{2\sqrt{\sigma}}\ln\frac{x_{f0}}{x} - \frac{\sigma}{\sqrt{2}}\right)\right] +$$

$$+ \frac{R_{oz1} - R_{oz2}}{2}\left[1 + erf\left(\frac{1}{2\sqrt{\sigma}}\ln\frac{x_f}{x} - \frac{\sigma}{\sqrt{2}}\right)\right] +$$

$$+ \frac{R_{oz2} - R_0}{2}\left[1 + erf\left(\frac{1}{2\sqrt{\sigma}}\ln\frac{x_{f1}}{x} - \frac{\sigma}{\sqrt{2}}\right)\right] + R_0 .$$

4 Solutions of inverse problems

The interpretation procedure of logging data is reduced to minimization of mean-square deviation of measured data from theoretical curve assigned by formula (1). The goal is achieved by matching of initial data for system of hydrodynamic and salt-exchange equations, in other words by means of solution of inverse problems. For instance data interpretation are shown for real well on fig. 6. Location of displacement fronts corresponds to case (A) for the well. There are values of maximal deviation *Dev* and mean-square deviation *Sq* on the right. Broken line presents values of real resistivity near borehole, r_f and r_{f0} are locations of displacement fronts of oil and gas, r_{oz} is radius of low-resistivity zone (r_{f1} is the same), r_n is radius of volume mud filtrate invasion, s_0 and s_{00} are obtained initial oil and gas saturations, consecutively. The location of displacement fronts correspond to case (A).

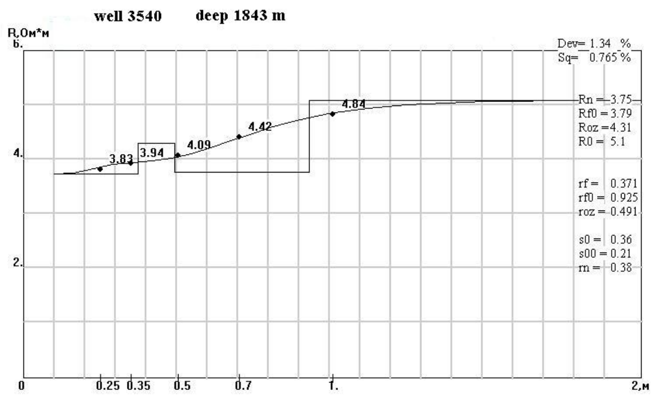

Fig. 6. Example of sounding data interpretation.

Similar interpretation of electromagnetic sounding data is shown on fig. 7. Here positions of radii of fronts are right as for case (B).

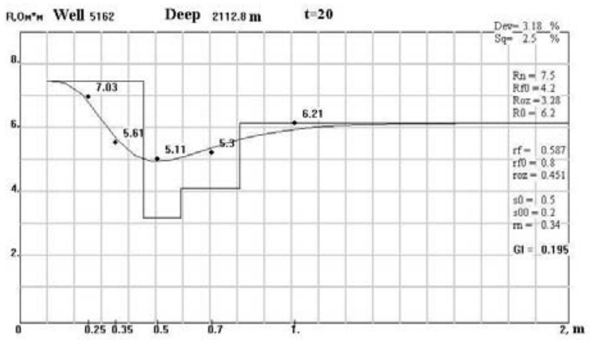

Fig. 11. Example of sounding data interpretation.

5 Conclusion

Focusing properties of the HFIIL tool confirm the appropriate use of log-normal probability frequency distribution. It is shown that the centres of sensitivities locate on distances from well axe equaled about half of length between generative coils and farthest measuring coils for accepted constructive parameters of three-coil sondes.

The results of modeling corroborate that locations of displacement fronts and radius of low-resistivity zone are defined by initial hydrocarbon phase saturation. Hydrodynamic characteristics such as initial saturation by hydrocarbon phases, volume drilling mud filtrate ingress depth and locations of displacement fronts were defined for real wells.

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