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ВЛИЯНИЕ ТЕПЛООБМЕНА НА ЯМР КАРОТАЖ ВО ВРЕМЯ БУРЕНИЯ

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Исследовалось влияние температуры на ядерный магнитно-резонансный (ЯМР) каротаж во время бурения. Изучались как влияние теплопередачи, так и влияние проницаемости в зоне проникновения бурового раствора Аналитические решения и численные расчеты были проверены на примере полевых данных ЯМР-каротажа во время бурения.

Ключевые слова: ЯМР каротаж во время бурения, влияние теплопередачи, влияние проницаемости.

HEAT EXCHANGE IMPACT ON NMR LOGGING WHILE DRILLING

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The effect of temperature on nuclear magnetic resonance (NMR) logging while drilling (LWD) has been studied. Heat conduction and permeability effects in the near wellbore invasion zone have been taken into account. Analytical solutions and numerical calculations have been exemplified and verified with the use of NMR LWD field data.

Key words: NMR logging while drilling, heat transfer effect, permeability effect.

Introduction

Temperature affects nuclear magnetic resonance (NMR) measurements acquired by well logging. Both nuclear spin magnetization and NMR signal are inversely proportional to the absolute temperature (Curie-Langevin law). In a magnetic field $\vec{B}_0$, a macroscopic magnetization $\vec{M}_0(\vec{r})$ of a unit volume in thermal equilibrium state is described by:

$$\vec{M}_0(\vec{r}) = n(\vec{r})\frac{\gamma^2\hbar^2}{3kT}S(S+1)\cdot\vec{B}_0, \tag{1}$$

where $n(\vec{r})$ is the number of magnetic nuclei per unit volume, $\vec{r}$ is the position vector, $\gamma$is the gyromagnetic ratio for protons, S=1/2 is the nuclear spin, $\hbar$ and k are Planck and Boltzmann constants, respectively, and T is the absolute temperature of the formation [1].

In both wireline NMR logging and NMR logging while drilling (LWD) the measured mud temperature on signed level is used as a proxy temperature of the NMR sensitive volume situated several centimeters deep into the formation from the borehole surface. In NMR LWD (in contrast to wireline NMR logging) the temperature of the mud and the near-wellbore formation can be significantly different from the temperature of the native formation. This can occur if during drilling operations the circulating mud temperature is not in equilibrium with the surrounding formation temperature. The temperaturedifference will bias the NMR-derived porosities, but a correction of this effect is not yet a standard procedurein MMR LWD [2].

Theory

For NMR LWD temperature correction, we have to estimate the temperature in the NMR sensitive volume and compare it to the temperature of the mud, which under certain circumstances may be cooler or warmer as the formation. Since the sensitive volume is situated only several centimeters into the formation from the borehole wall [3], the near well-bore temperature behavior needs to be investigated as a function of mud temperature, formation properties, and time.

A heat conduction equation in cylindrical coordinate frame is

$$\frac{\partial T}{\partial t} = D_T\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial T}{\partial r}\right), \tag{2}$$

where D_T is the rock thermal conductivity. For dimensionless parameters $\tau_T = D_T\, t/a^2$ and $\rho = r/a$ (where a is the borehole radius), the solution of the heat conduction equation with initial and boundary conditions ($T(\tau_T,1) = T_1(\tau_T)$, $T(0,\rho) = T_0(\rho)$) for $\tau_T > 0$ and $\rho > 1$ is

$$T = \int_0^\infty e^{-\tau_T u^2} K_0(\rho,u) \cdot \left\{ \int_1^\infty T_0(\rho) \cdot K_0(\rho,u)\rho\, d\rho - \frac{2}{\pi} \cdot \frac{\int_o^{\tau_T} e^{\tau_T u^2} f(\tau_T) \cdot d\tau_T}{\sqrt{J_0^2(u) + Y_0^2(u)}} \right\} u\,du \tag{3}$$

$$K_0(\rho,u) = \frac{J_0(u\rho) \cdot Y_0(u) - Y_0(u\rho) \cdot J_0(u)}{\sqrt{J_0^2(u) + Y_0^2(u)}}$$

where J_0 and $Y_0$are Bessel and Neumann functions [4].

For constant initial and boundary conditions ($T_1 = const$, $T_0 = const$) the analytical solution is more simple:

$$\frac{T - T_0}{T_1 - T_0} = 1 + \frac{2}{\pi} \int_0^\infty exp(-\tau_T u^2) \frac{J_0(u\rho)Y_0(u) - Y_0(u\rho)J_0(u)}{J_0^2(u) + Y_0^2(u)} \cdot \frac{du}{u} \tag{4}$$

And a small-times expansion is

$$\frac{T - T_0}{T_1 - T_0} \approx \frac{1}{\sqrt{\rho}} \cdot erfc\left(\frac{\rho - 1}{2\sqrt{\tau_T}} \right) \tag{5}$$

Fig. 1 compares the solutions (4) and (5) for parameter values typical for NMR LWD conditions: τ_T=0.3, 1, 3 (for D_T =0.01cm^2/s, t=3600s, and a=10.8 cm τ_T=0.3). This shows that the small-times expansion (5) can be used for NMR LWD temperature correction at times of NMR measurement since drilled in the order of 1 hour.

The heat conduction equation considering mud invasion is $\frac{\partial T}{\partial t} = div\left(D_T \cdot gradT - \vec{v} \cdot T\right)$, where $\vec{v}$is the rate of mud filtration through the near-wellbore formation. In a cylindrical coordinate frame for constant radial flux $\vec{v} = \frac{v_0 \cdot a}{r} \cdot \vec{e}_r$ (v_0= const is the filtration flow rate at $r=a$, $\vec{e}_r$ is the unit vector along radius r). In dimensionless form with $\beta = v_0 a / 2D_T$ we have $\frac{\partial T}{\partial \tau_T} = \frac{\partial^2 T}{\partial \rho^2} + \frac{1 - 2\beta}{\rho} \cdot \frac{\partial T}{\partial \rho}$. For constant initial and boundary conditions ($T_1 = const$, $T_0 = const$) the solution for $\rho > 1$ and $\tau_T > 0$ is

$$\frac{T - T_0}{T_1 - T_0} = 1 + \frac{2\rho^\beta}{\pi} \int_0^\infty exp(-\tau_T u^2) \cdot \frac{J_\beta(u\rho) \cdot Y_\beta(u) - Y_\beta(u\rho) \cdot J_\beta(u)}{J_\beta^2(u) + Y_\beta^2(u)} \cdot \frac{du}{u} \tag{6}$$

where J_β and Y_β are Bessel and Neumann functions.The convection parameter β has to be obtained from solving the filtration problem.

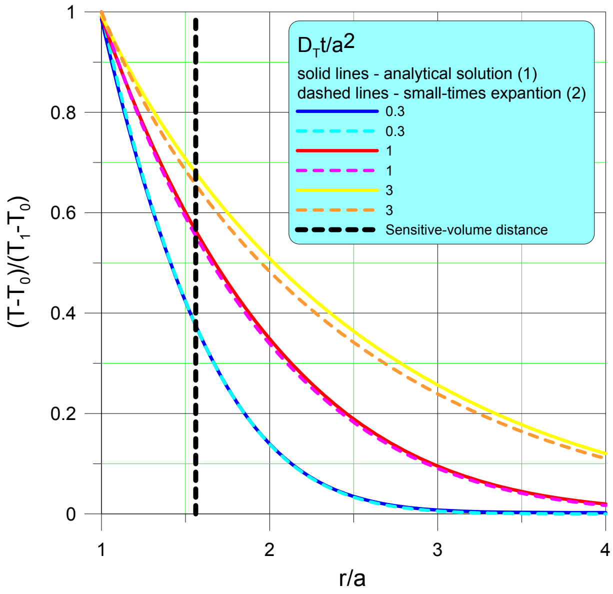

Fig. 1. A comparison of the exact solution (4) and its approximation (5) for τ_T=0.3, 1, 3

The conduction equation for the pore pressure P in a cylindrical coordinate frame for dimensionless $\tau_P = D_P\, t/a^2$ (where $D_P = k/(\eta\varepsilon\varphi)$ is the piezo-conductivity coefficient, k is permeability, η is viscosity, φ is the porosity of the movable fluid in the pores, and ε is the formation compressibility) is $\frac{\partial P}{\partial \tau_P} = \frac{\partial^2 P}{\partial \rho^2} + \frac{1}{\rho}\cdot\frac{\partial P}{\partial \rho}$. For initial and boundary conditions ($P(\tau_P,\rho) = P_1 = const$, $P(0,\rho) = P_0 = const$) the solution for $\rho > 1$ and $\tau_P > 0$ is similar to [4] with T replaced by P. The mud-filtration rate, thus, is

$$v_0 = -\frac{k}{\eta}\cdot\frac{\partial P}{dr}\bigg|_{r=a} = \frac{k}{\eta}\cdot\frac{P_1-P_0}{a}\left(\frac{2}{\pi}\right)^2\int_0^\infty \frac{exp(-\tau_P u^2)\cdot du}{J_0^2(u)+Y_0^2(u)} \tag{7}$$

And the convection parameter β takes the form

$$\beta = \frac{k}{\eta}\cdot\frac{P_1-P_0}{2D_T}\left(\frac{2}{\pi}\right)^2\int_0^\infty \frac{exp(-\tau_P u^2)\cdot du}{J_0^2(u)+Y_0^2(u)}. \tag{8}$$

Fig. 2 compares the mud-filtration rate (7) for different rock permeabilities k =1, 10, 100md.

Fig. 3 compares the behavior of the convection parameter βderived by (8) for different permeabilities k=1, 10, 100 md, illustrating its sensitivity to rock permeability. Only in a high permeability rockthe parameter β varies significantly versus time.For LWD measurementsthis corresponds to the time since drilled with mud circulating through the borehole.

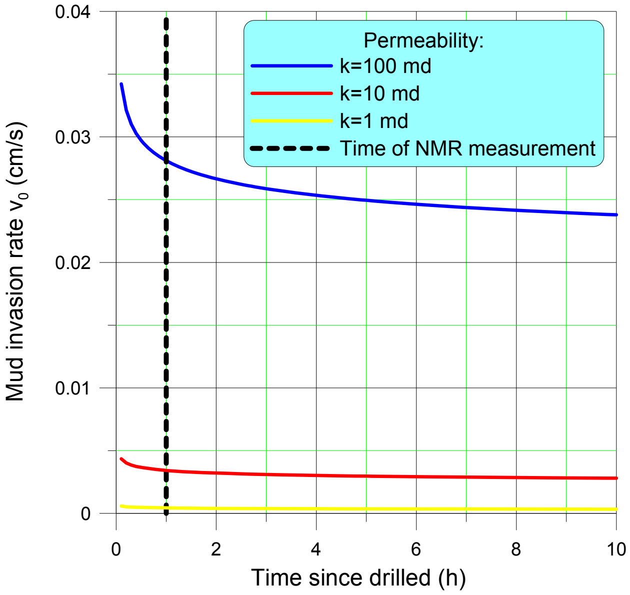

Fig. 2. Comparison of the mud-filtration rate for different permeabilities k =1, 10, 100 md

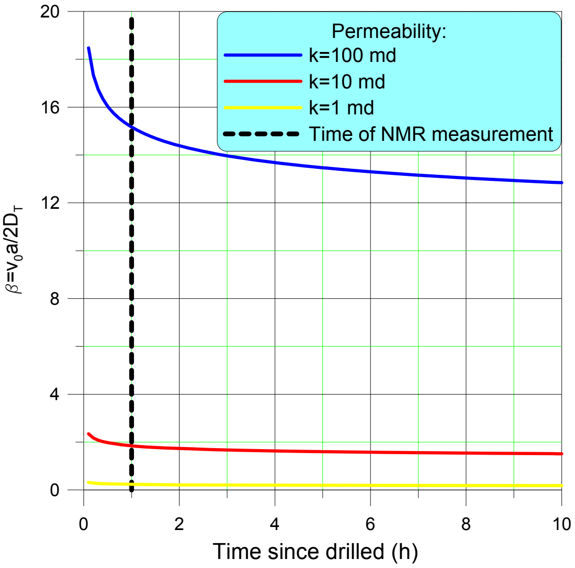

Fig. 3. Comparison of the convection parameter β for different permeability k=1, 10, 100 md

Fig. 4 compares the solution (6) for temperature versus distance from the borehole axis with the parameters values: τ_T=0.3,k=0 (β=0), k=1 (β=0.25), k=10 (β=2), k=100 (β=17). The black dashed line represents the location of the NMR sensitive volume in the formation.

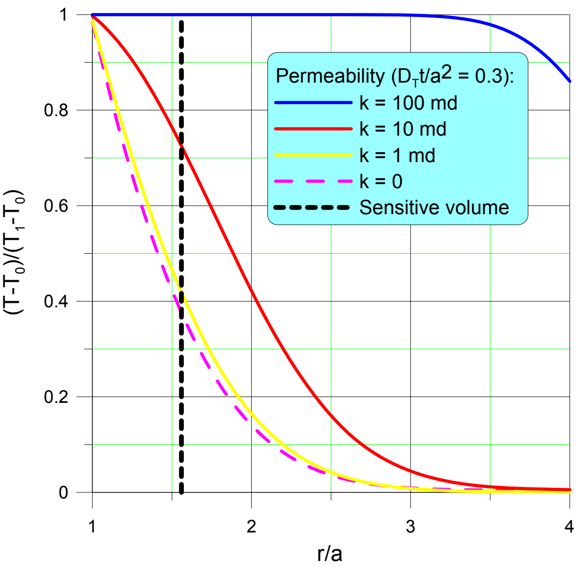

Fig. 4. Comparison of the temperature versus distance from the borehole axis for different permeabilities k = 1, 10, 100 md

Fig. 5 compares the solution (6) for temperature versus time since drilled with the parameters: τ_T=0.3, k =0 (β =0), k =1 (β =0.25), k =10 (β =2), k =100 (β =17). Fig. 4 and 5 show that for low permeability the near-wellbore temperature, which may be strongly affected by the mud temperature, starts to equilibrate with the formation temperature. This reduces the temperature effect on the NMR measurement and the resulting porosity bias. For high permeability, the mud is also invading into the formation. This counteracts the temperature equilibration process, resulting in a larger temperature difference and a larger porosity bias. Therefore, the required NMR signal correction will be larger in formations with high permeability.

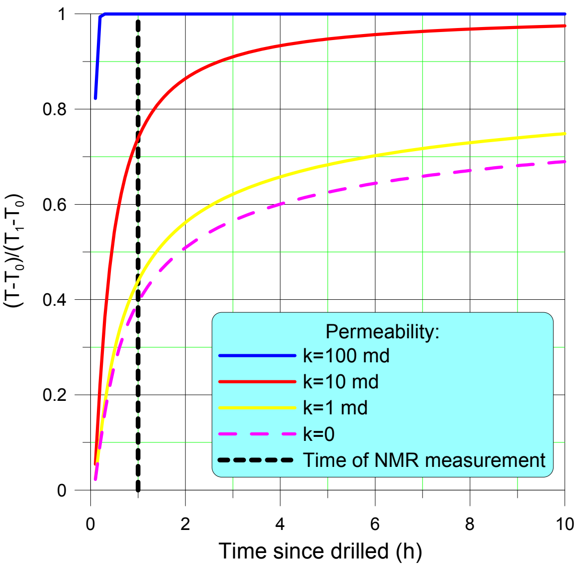

Fig. 5. Comparison of the temperature versus time since drilled for different permeabilities k=1, 10, 100 md at the location of the NMR sensitivevolume (compare Fig. 4)

Application

Fig. 6 exemplifies the effect of temperature on a short NMR LWD echo train acquired in a shale zone with low permeability. Fig. 6 a) shows the measured temperature in the borehole, the formation temperature estimated using an expected geothermal gradient, and the temperature of NMR LWD sensitive volume calculated by our model at different borehole vertical depths. The data have been obtained with a rate of penetration (ROP) of 20 m/h, and a bit-sensor offset (the distance between bit and the NMR LWD sensor) of 20 m, which leads to a time since drilled of 1 hour. The parameters used for the temperature modeling are: the borehole diameter is 8.5 in, the sensitive-volume diameter is 13.2 in, the thermal diffusivity D_T is 10^{-2} cm^2/s, the viscosity η is 10^{-2} poise, the compressibility ε is $5 \cdot 10^{-2}$ Pa^{-1}, φ=20%, the pressure difference P_1-P_0 is 20 atm, and the geothermal gradient is 3K/100m.

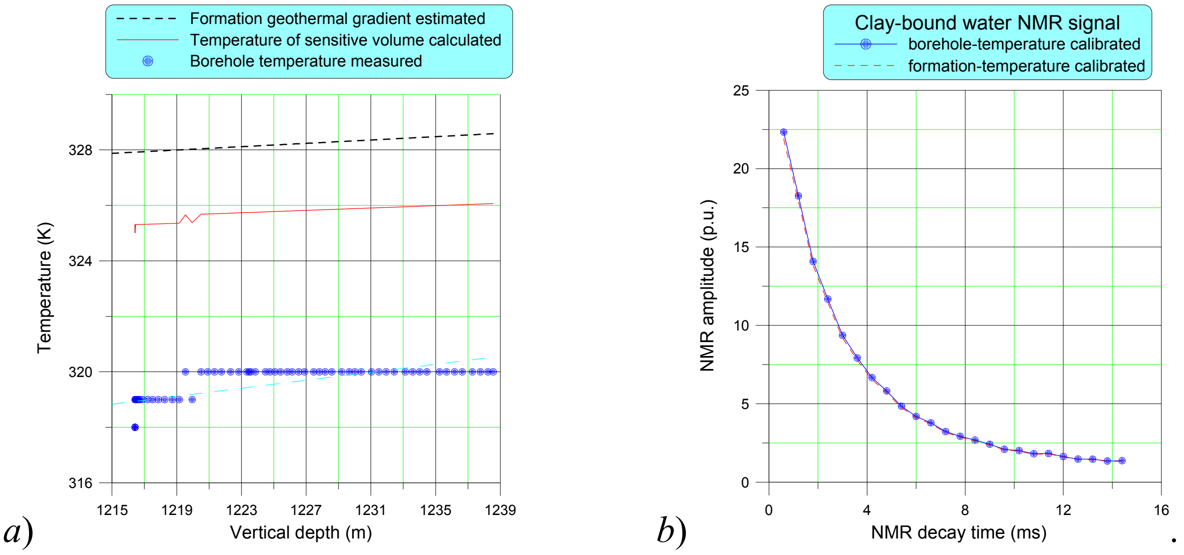

Fig. 6. *a*) Temperature of borehole, formation, and sensitive volume vs vertical depth, *b*) temperature effect on NMR LWD signal at vertical depth 1215m to1239m

The resulting effect of temperature on the NMR LWD echo amplitude shown in Fig. 6 b) is 2%. It is caused by the 6 K difference between the temperature measured by the tool and the temperature calculated for the formation at the sensitive volume. The resulting change in porosity (e.g., 0.5 pu for a formation with 25 pu) is below the accuracy of the measurement of ±1 pu and, therefore, can be neglected. If the initial temperature difference is larger or time since drilled is decreased (e.g., by higher ROP), the temperature effect will become significantly larger and the NMR porosity bias and its correction will become relevant.

Fig. 7 presents data from the same borehole as Fig. 6 but for a longer depth interval including permeable layers between 1600 and 1700 m. For the permeable layers the temperature of the NMR LWD sensitive volume is equal to the temperature measured in the borehole. The average temperature difference is 8 K, resulting in an average temperature difference between the tool and the sensitive volume of 5 K. Only in the high permeability layers between 1600 and 1700 m (Fig. 7), the calculated temperature in the sensitive volume is up to 8 K different from the tool. For a 25 pu formation this causes a bias of 0.6 pu, which is below the accuracy of the NMR measurement. The effect will become more relevant for larger temperature difference, but a correction with this method can also be applied in this situation.

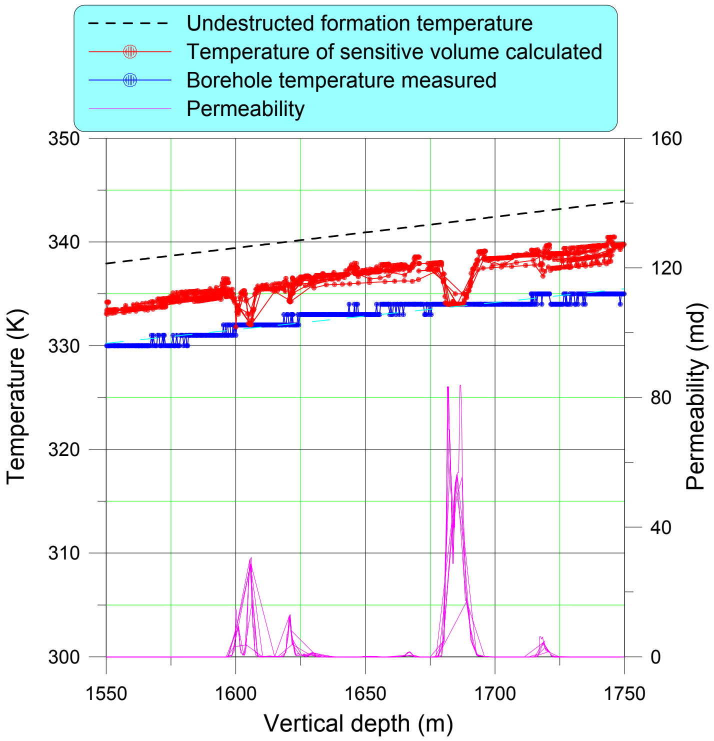

Fig. 7. Temperature of borehole, formation, and sensitive volume, andpermeability measured by NMR LWD versus the borehole vertical depthwith permeable layers between 1550 and 1750 m. Note the effect of the permeable layers on the calculated temperature at the NMR sensitive volume

Summary

This publication presents an analytical approach for the estimation of the NMR LWD temperature effect. The model applies when the temperature measured in the logging tool (i.e., in the borehole) is different from the actual formation temperature. In addition, to the heat transport through the formation, it includes the treatment of convective heat transfer for permeable layers invaded by mud filtrate. The theoretical results show that the heat transfer with convection is sensory adaptive to permeable layers. Due to the mud invasion in permeable zones, the temperature of NMR LWD sensitive volume is close to the measured temperature in the borehole, i.e., the mud temperature. Based on the results, a temperature effect correction for NMR LWD data can be implemented and conducted during standard NMR LWD data processing.

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