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A NEW TECHNIQUE FOR DETERMINING THE FORMATION'S THERMAL CONDUCTIVITY BASED ON THE CYLINDRICAL PROBE WITH A CONSTANT HEAT FLOW RATE

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Summary. The thermal conductivity of geological formations is a parameter used to estimate the terrestrial heat flow and the geothermal energy resources. This parameter is also essential in environmental studies and the search for hydrocarbons and underground water reserves. A new technique has been developed to determine thermal conductivity formation by constant heat flow.

Earlier, Eppelbaum and Kutasov (2013) analyzed the case of the cylindrical probe with a variable heat flow rate. However, as indicated by experience, in geophysical practice, frequently observed situations have constant (or quasi-constant) heat flow rates. This statement simplifies calculations and allows for more accurate results. It is assumed that core samples or cuttings could determine dry formation density, porosity, and pore fluid saturations. In this case, the volumetric specific heat of formations can be estimated. It is also assumed that the transient temperature-time data are available for a cylindrical probe with a constant heat flow rate placed in a wellbore. The widely known Newton method was used to solve the problem. A semi-analytical equation describing the temperature of the probe wall is used to determine the formation conductivity. The formation thermal diffusivity is also calculated. Finally, a simulated example is presented.

Keywords*: thermal conductivity, thermal diffusivity, cylindrical probe, constant heat flow rate*

Introduction

The thermal conductivity of formations is an essential parameter needed to estimate the terrestrial heat flow, geothermal energy heat resources, environmental studies, and hydrocarbon and underground water prospecting (Eppelbaum et al., 2014; Li et al., 2016; Tomaškovičová and Ingeman-Nielsen, 2024). Knowledge of thermal properties of rocks and soils is required to evaluate the heat exchange in boreholes, underground pipelines, and surrounding formation systems. In natural conditions (*in situ*), thermal parameters depend on pressure and temperature (e.g., Koven et al., 2013; Eppelbaum et al., 2014; Liu et al., 2016; Boike et al., 2021). However, in practice, thermal parameters of formation are usually obtained from laboratory measurements (e.g., Kappelmeyer and Haenel, 1974; Pascuale et al., 2011; Popov et al., 2011; Dalla Santa et al., 2020). Earlier, a semi-theoretical equation was suggested to approximate the dimensionless heat flow rate from an infinite cylindrical source with a constant bore-face temperature. This equation was used to develop a technique for *in situ* evaluation of the values of formation thermal conductivity and thermal resistance of the borehole expressed through the skin factor (Kutasov and Kagan, 2003). It was assumed that core samples or cuttings could determine dry formation density, porosity, and pore fluid saturations. The specific heat and density of formations can be estimated in this case. Calculations conducted by Mufti (1971) revealed that a cylinder whose length is five times or more its diameter could be treated as an infinite cylinder for practical purposes. In this case, the heater can be considered an infinite cylindrical heat source.

It is necessary to note that earlier, Eppelbaum and Kutasov (2013) considered the case of the cylindrical probe with a variable heat flow rate. However, as indicated by geophysical experience, frequently observed situations have constant (or quasi-constant) heat flow rates in practice. This assumption simplifies calculations and allows for obtaining more exact results.

The paper is only objective in suggesting a new technique for determining the formation of thermal conductivity using a cylindrical probe with a constant heat flow rate placed in the wellbore. It is assumed that the volumetric specific heat of formations can be determined from core samples or cuttings. The next step in validating the proposed technique is to conduct several field or laboratory tests and compare the results of these tests with those obtained by utilizing the proposed method.

Effective radius of the heater

We will use the effective radius concept to consider the effect of the probe casing and the contact thermal resistance on probe temperature. This approach is widely used in transient pressure and flow well testing (e.g., Earlougher, 1977; Kutasov and Eppelbaum, 2015) to evaluate the effect of formation damage (improvement) around the borehole on the pressure at the borehole's wall. Firstly, we introduce a skin factor (**s**) – the parameter that quantitatively determines the effect of the well's thermal resistance on the heat flow rate. In our case

$$s=\left(\frac{\lambda}{\lambda_{\text{ef}}}-1\right)\ln\frac{r_w}{r_h} \quad , \tag{1}$$

where r_h is the radius of the heater, and λ_{ef} is the effective thermal conductivity of the $(r_w - r_h)$ annulus.

For an open (uncased) borehole, the $(r_w - r_h)$ annulus is filled with the drilling fluid (or air) and mud cake – a plastic coating of the borehole resulting from the solids in the drilling fluid adhering and building up on. The $(r_w - r_h)$ ring in the cased borehole comprises drilling fluid, steel, and cement. It is more convenient to express the skin factor through the apparent (effective) heater radius (Earlougher, 1977).

$$r_{ha}=r_h\exp(-s), \tag{2}$$

where r_{ha} is the effective radius of the heater.

Semi-analytical equation of cylindrical source with a constant heat flow rate

In this case, the transient temperature is a function of time, thermal conductivity, and volumetric heat capacity of formations. To determine the temperature T_w $(t, r = r_h)$, it is necessary to obtain the solution of the diffusivity equation under the following boundary and initial conditions:

$$T(t=0,r)=T_i, \qquad r_h \le r < \infty, \tag{3}$$

$$\left(r\frac{\partial T}{\partial r}\right)_{r_h}=-\frac{q}{2\pi\lambda}, \qquad T(t,r\to\infty)\to T_i, \qquad t>0, \tag{4}$$

where T_i is the formation temperature, λ is the thermal conductivity of formation, q is the heat flow rate per unit length, and rh is the radius of the heater.

It is well known that, in this case, the diffusivity equation has a solution as a complex integral form with Bessel functions (Carslaw and Jaeger, 1959). In our previous work, we obtained the following semi-analytical equation (Kutasov and Eppelbaum, 2015) for the wall transient temperature

$$\Delta T=T_w-T_i=\frac{q}{2\pi\lambda}\ln\left[1+\left(c-\frac{1}{a+\sqrt{t_D}}\right)\sqrt{t_D}\right], \tag{5}$$

$$t_D=\frac{\chi t}{r_h^2}=\frac{\lambda t}{c_p\rho r_h^2},$$

$$a = 2.7010505, \qquad c = 1.4986055,$$

where ρ is the density of formations, c_p is the specific heat at constant pressure, χ is the thermal diffusivity of formation, and t_D is the dimensionless heating time.

Working equation

Let us assume that at least two temperature readings were taken at $t = t_1$ and $t = t_2$, and $s \neq 0$, then

$$\Delta T_1=T_{w1}-T_i=\frac{q}{2\pi\lambda}\ln\left[1+\left(c-\frac{1}{a+\sqrt{t_{D1}}}\right)\sqrt{t_{D1}}\right], \tag{6}$$

$$t_{D1}=\frac{\chi t_1}{r_{ha}^2}, \tag{7}$$

$$\Delta T_2=T_{w2}-T_{i_i}=\frac{q}{2\pi\lambda}\ln\left[1+\left(c-\frac{1}{a+\sqrt{t_{D1}b}}\right)\sqrt{t_{D1}b},\right.$$

$$\left. b=\frac{t_2}{t_1}\right] \tag{8}$$

Combining Eqs. (6) and (8), we obtain

$$\gamma = \frac{\Delta T_2}{\Delta T_1} = \frac{\ln\left[1+\left\{c-\frac{1}{a+\sqrt{t_{D1}b}}\right\}\sqrt{t_{D1}b}\right]}{\ln\left[1+\left\{c-\frac{1}{a+\sqrt{t_{D1}}}\right\}\sqrt{t_{D1}}\right]}. \quad (9)$$

Thus, we can estimate the dimensionless time t_{D1} from the last equation.

After this, the thermal conductivity of formations can be obtained from Eq. (6) or Eq. (8). The thermal diffusivity of formations is estimated from the following relationship

$$\chi = \lambda / C_v , \quad (10)$$

where C_v is the volumetric specific heat. The effective heater radius and the skin factor are calculated from Eqs. (2) and (7). Finally, the value of λ_{ef} is obtained from Eq. (1)

$$\lambda_{ef\ i} = \frac{\lambda \ln \frac{r_w}{r_h}}{s + \ln \frac{r_w}{r_h}}. \quad (10)$$

Data processing

To utilize the developed software to determine the value of t_{D1}, Eq. (6) should be rewritten as

$$\varepsilon = \gamma - \frac{\ln\left[1+\left\{c-\frac{1}{a+\sqrt{t_{D1}b}}\right\}\sqrt{t_{D1}b}\right]}{\ln\left[1+\left\{c-\frac{1}{a+\sqrt{t_{D1}}}\right\}\sqrt{t_{D1}}\right]}, \quad (11)$$

where ε is a small value and depends on the accuracy of the temperature ratio χ.

The known Newton's method was used to solve Eq. (11) (Grossman, 2014). This method seeks a solution to an equation by defining a sequence of numbers that become successively closer and closer to the solution. The conditions guarantee that Newton's method, in our case, will work and provide a unique solution, and that the results are satisfactory (Grossman, 2014). In the subroutine that utilizes Newton's method for the following simulated example, these parameters were used: (a) the starting value of the dimensionless time is 0.0001; (b) the time increment is 2.0, and (c) the absolute accuracy of the temperature ratio is **e =** 0.0001.

Simulated example

A metallic electrical heater is placed into a vertical open (uncased) borehole. The heater operated for 10 hours, and the transient temperature of the heater was recorded (Table 1). The well radius is $r_w = 0.10$ m, and the probe's radius is $r_h = 0.08$ m. The $(r_w - r_h)$ annulus consists of the mud cake and drilling fluid. It is assumed that the effective thermal conductivity of the $(r_w - r_h)$ annulus is $\lambda_{ef} = 1.099$ W/(m·K). The heat flow rate per unit of length is 36.75 W/(m·K). The volumetric specific heat of sandstone formation is $C_v = 2288.2$ Joule/(m^3·K), and the thermal conductivity $\lambda = 2.198$ W/(m·K). Using Eqs. (6) or (8), the data of this simulated example were generated (Table 1, columns 1 and 2). The results of calculations using Eqs. ((1) – (11)) are presented in Table 1. Indeed, the assumed and calculated values of thermal conductivity **λ** and diffusivity **χ** are in perfect agreement. This example shows that the basic Eq. (5) can effectively be used to calculate thermal conductivity and thermal diffusivity of formations.

Table 1

Input data and calculation results. The assumed parameters: χ = 0.003456 m^2/hr, λ = 2.198 W/(m·K)

Numbers of models	t_2, hrs	ΔT_1, °C	ΔT_2, °C	χ, m^2/hr	λ, W/(m·K)
1	2.0 3.0 5.0	2.0039 2.0039 2.0039	2.5660 2.9365 3.4436	0.003457 0.003456 0.003456	2.199 2.198 2.198
2	4.0 6.0 8.0	2.5660 2.5660 2.5660	3.2168 3.6346 3.9458	0.003456 0.003456 0.003455	2.198 2.198 2.198
3	6.0 6.0 10.0	2.9365 2.9365 2.9365	3.6346 3.9458 4.1947	0.003456 0.0034555 0.0034556	2.198 2.198 2.198
4	8.0 10.0	3.2168 3.2168	3.9458 4.1947	0.0034552 0.0034554	2.198 2.198
5	10.0	3.4436	4.1947	0.0034554	2.198

Conclusions

A novel method to determine thermal conductivity and diffusivity in situ formation is developed. This method is based on the enhanced semi-analytical equation approximating the wall temperature of a transient heater from an infinitely long cylindrical source with a constant heat flow rate. The author suggests that applying this method will sufficiently increase the accuracy of the mentioned parameter in subsurface and deep boreholes where thermal parameters are observed. Field experiments in open and cased boreholes are needed to verify the applicability of the suggested method.

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НОВАЯ МЕТОДИКА ОПРЕДЕЛЕНИЯ ТЕПЛОПРОВОДНОСТИ ПЛАСТА НА ОСНОВЕ ЦИЛИНДРИЧЕСКОГО ЗОНДА С ПОСТОЯННОЙ СКОРОСТЬЮ ТЕПЛОВОГО ПОТОКА

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Резюме. Теплопроводность геологических формаций является параметром, используемым для оценки земного теплового потока и геотермальных энергетических ресурсов. Этот параметр также имеет важное значение при изучении окружающей среды и поиске месторождений углеводородов и запасов подземных вод. Разработана новая методика определения теплопроводности в скважинах при наличии постоянного теплового потока. Ранее Эппельбаум и Кутасов (2013) проанализировали случай цилиндрического зонда с переменной скоростью теплового потока. Однако, как показывает опыт, в геофизической практике часто наблюдаются ситуации с постоянными (или квазипостоянными) скоростями теплового потока. Это гипотеза упрощает расчеты и позволяет получить более точные результаты. Предположим, что образцы керна или шлама, полученные из отбора образцов, могут определить плотность сухого пласта, пористость и насыщенность порового флюида. В этом случае можно оценить объемную удельную теплоемкость геологических образований. Предполагается, что данные о переходной температуре и времени доступны для цилиндрического зонда с постоянным тепловым потоком, размещенного в стволе скважины. Для решения этой задачи был использован широко известный метод Ньютона. Для определения проводимости пласта использовано полуаналитическое уравнение, описывающее температуру стенки зонда. Также рассчитывается температуропроводность пласта. Представлен модельный пример, который показывает прекрасную сходимость результатов.

Ключевые слова*: теплопроводность, температуропроводность, цилиндрический зонд, постоянный тепловой поток*

DAİMİ SÜRƏTLİ İSTİLİK AXINI VASİTƏSİLƏ YARANAN SİLİNDRİK ZOND ƏSASINDA LAYIN İSTİLİK KEÇİRİCİLİYİNİN MÜƏYYƏNLƏŞDİRİLMƏSİNİN YENİ ÜSULU

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Xülasə. Geoloji formasiyaların istilik keçiriciliyi yerin istilik axını və geotermal enerji ehtiyatlarının qiymətləndirilməsi üçün istifadə olunan parametrdir. Bu parametr həmçinin ətraf mühitin öyrənilməsi və karbohidrogen yataqlarının və yeraltı su ehtiyatlarının axtarışında mühüm əhəmiyyət kəsb edir. Daimi istilik axını olan quyularda istilikkeçirmənin müəyyən edilməsi üçün yeni metodika işlənib hazırlanmışdır. Daha əvvəl Eppelbaum və Kutasov (2013) istilik axınının dəyişən sürəti ilə silindrik zond vəziyyətini təhlil etmişlər. Lakin təcrübə göstərir ki, geofiziki praktikada daimi (və ya kvazi daimi) istilik axını halları tez-tez müşahidə olunur. Bu fərziyyə hesablamaları sadələşdirir və daha dəqiq nəticələr əldə etməyə imkan verir. Fərz edək ki, nümunələrin seçilməsindən əldə edilən kern və ya şlam quru layın sıxlığını, məsaməli flüidin möhkəmliyini və doyma dərəcəsini təyin edə bilər. Bu halda geoloji törəmələrin xüsusi istilik tutumunun həcmini qiymətləndirmək olar. Güman olunur ki, daimi istilik axınına malik olan silindrik zond üçün keçid temperaturu və zamanı quyunun gövdəsində yerləşir. Bu problemi həll etmək üçün Nyutonun geniş tətbiq olunan metodundan istifadə edilmişdir. Layın keçiriciliyini müəyyən etmək üçün zond divarcığının temperaturunu əks etdirən yarımanalitik tənlikdən istifadə edilmişdir. Həmçinin layın temperatur keçiriciliyi hesablanır. Nəticələrin mükəmməl uyğunluğunu göstərən model nümunəsi təqdim olunur.

Açar sözlər: *istilik keçiriciliyi, temperatur keçiriciliyi, silindrik zond, daimi istilik axını*