Chapter

Modeling of Thermal Conductivity in Gas Field Rocks

Chis Timur, Jugastreanu Cristina, Tabatabai Seyed Mehdi and Renata Radulescu

Abstract

The thermal conductivity of rocks is a property necessary to be determined at the beginning of the exploitation of oil and gas deposits, both for the design of secondary extraction (hot water injection, steam) and for the development of tertiary extraction technologies (CO_2 injection, injection flue gas, and initiation of underground combustion). In this chapter, we present a new method for determining the thermal conductivity of rocks and we also analyzed the relationships between this parameter and the properties of oil and gas collector rocks (density, porosity).

Keywords: thermal, conductivity, oil, gas, fields, rocks, properties

1. Introduction

The need to discover new deposits of useful mineral substances led to the study of the physicochemical properties of the soil and subsoil constituents (geological layers).

From the beginning of the geophysical research of the subsoil, the knowledge of the temperature of rocks and constituent fluids was an absolutely necessary step to establish working conditions in tunnels and mine shafts (to prevent the formation of explosive mixtures and explosions) [1].

Subsequently, the geothermal phenomena (geothermal gradient and geothermal stage) were analyzed, in order to improve the exploitation of oil and gas deposits [2].

Knowing the geothermal flow of geological layers was useful for determining the temperature of the crust and the structure of the lithosphere and also for understanding how to form oil and gas deposits.

The exploitation of crude oil and gas from the Moesic Platform in Romania has created a database regarding the understanding of the thermals of geological strata and especially the formation of oil deposits in magmatic fields [3, 4].

Theoretical and practical aspects of the use of geothermal steps in the analysis of deposits of useful mineral substances were made by Dowle and Cobb [5].

The interest in determining the geothermal of the subsoil and in particular the geothermal of the oil and gas deposits were due to the following [6–8]:

a. Research into the evolution of the temperature of geological structures in order to recover heat and produce renewable energy,

b. Determining the mode of secondary and tertiary recovery of oil for the application of methods for the injection of flue gas, steam, hot water, and CO_2 into the field,

c. The need to determine the geological period for the formation of oil and gas deposits and the optimal way to extract them,

d. Analysis of the evolution of the waterfront in oil and gas fields,

e. Research on ways to isolate geological layers by cementation.

The calculation of the thermal flow was performed by determining the thermal gradients and thermal conductivity in measurement points and subsequently by determining in the laboratory the physical properties of the rocks (cores) collected from geological research drilling [9].

The determined values had an estimative character (being often point values), but they were useful in determining the thermal structure of the geological layers [10].

Thus, following the measurements of the temperature of the oil fluid extraction wells, a low thermal flux was determined (45–57 mW/m^2 and 33–58 mW/m^2) in the areas rich in gas deposits and quite high in the areas with coal deposits (200 mW/m^2).

But the most important physical property of rocks and the constituent fluids of oil and gas deposits, namely thermal conductivity, is very useful in establishing the tertiary oil recovery system and in determining the flow of fluids through rock pores.

That is why this property is determined in the laboratory, by analyzing the heat transfer that passes through the rocks collected from the oil fields.

Thermal conductivity (k) is the property (ability) of rocks and continuous media to transmit, to a greater or lesser degree, thermal energy (relation 1) [11].

$$k = \frac{Q}{(t_2 - t_1) \bullet \left(\frac{s}{l}\right) \bullet \tau} [\mathrm{w/m\ °C}] \tag{1}$$

In Eq. (1), Q is the amount of heat that passes through rock with cross section s, in a time τ, and with a length l.

Factors influencing rock conductivity to take into account the structural-textural peculiarities of rocks (composition, size and orientation of rock granules, porosity, and fluid content), the temperature measured at the faces of the analyzed rocks (t_2, t_1), and the pressure to which the structure is subjected: geological analysis [12].

The conductivity of the rocks decreases as the size of the rock granules decreases because the number of contacts between the granules and the heat flux increases in the flow of fluids through the rock pores.

Also, the orientation of the rock granules influences their thermal conductivity, schistosity, stratification, and fracturing, reducing their values.

The thermal conductivity of dry porous rocks is lower than that of compact rocks (air with a thermal conductivity value of 0.55 mcal/cm°C s).

At the same time, the flow of fluids or the fluid content of rocks changes the value of thermal conductivity, and rocks with water have higher conductivity than those containing oil or natural gas.

The pressure in the geological layers not influences the values of thermal conductivity.

But the increase of the pressure increasing the conductivity due to the friction of the rock particles.

The increase in temperature leads to a decrease in conductivity due to the increase in the interaction speed of the particles of the crystal lattice.

The determination of the thermal conductivity of the rocks is necessary for the evaluation of the thermal flow of the deposit and especially for the choice of the most useful technology in increasing the recovery factor of crude oil and petroleum gases.

2. Measurement of rocks conductivity

The method of determining the thermal conductivity of rocks and constituent fluids is to measure the amount of heat that passes through a system consisting of two discs of known rocks (quartz) and which includes the rock disc under analysis (**Figure 1**).

The system is placed in a thermostatic bath, measuring the temperature difference between the three discs.

After reaching the thermal equilibrium, the values Q_1, Q_2, and Q_3 are almost equal and the heat transfer relation becomes [13]:

$$2Q_2 \cong Q_1 + Q_3 \tag{2}$$

As explained in relation 1, we obtain the value of thermal conductivity:

$$k_r = \frac{k_q \frac{\Delta t_1}{z_1} S_1 + k_q \frac{\Delta t_3}{z} S_3}{2 \frac{\Delta t_2}{z_2} S_2} \tag{3}$$

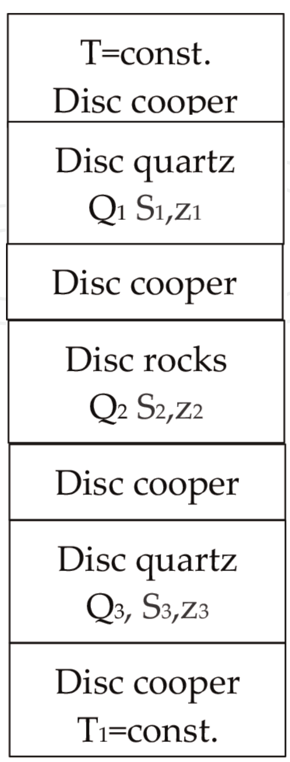

Figure 1.
Thermal conductivity measurement system (split bar method) [1, 9, 13].

where k_r is the thermal conductivity of the rock sample with cross section S_2 and thickness z_2, k_q is the thermal conductivity of quartz discs with cross section S_1, S_3 and thickness z_1, z_3.

The thermal conductivity of crystalline quartz can be determined by the relation [10, 12–14]:

$$k_q = \frac{1}{60{,}7 + 0{,}242t} \tag{4}$$

Figure 2 shows a device for determining the thermal conductivity by the plate method, with a single rock sample.

The mathematical model for determining the thermal conductivity of rocks in the exploitation areas of oil and gas deposits starts from the equation:

$$k_r = k_q\left(\frac{\Delta t_1 + \Delta t_3}{2\Delta t_2}\right)\left(\frac{z_2}{z}\,\frac{s}{s_2}\right) \tag{5}$$

where k_r is the thermal conductivity of the rock sample with cross section S_2 and thickness z_2, and k_q is the thermal conductivity of quartz discs with cross section S_1, S_3 and thickness z_1, z_3.

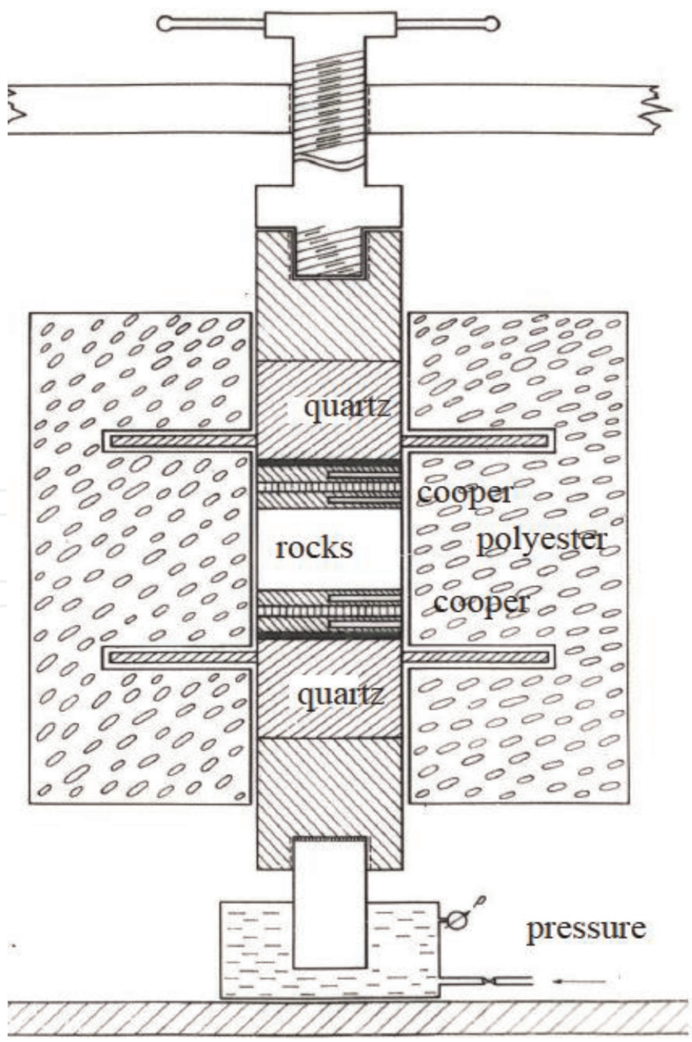

Figure 2.
Device for determining the thermal conductivity by the plate method, with a single specimen [9, 13, 14].

For ease of determinations, identical quartz dikes were made, and then:

$$S_1 = S_3 = S \tag{6}$$

$$z_1 = z_3 = z \tag{7}$$

Logarithming Eq. (5) we get:

$$log\, k_r = log\, k_q + \log(\Delta t_1 + \Delta t_3) - log\, 2 - log\, \Delta t_2 + log\, z_2 - logz + logs - log\, s_2 \tag{8}$$

To reduce the thermal resistance to the contact between the crucible and the analyzed rock, a thin layer of vaseline is used.

Another method for determining the thermal conductivity starts from the knowledge of the mineralogical composition and porosity.

Thus, knowing that rocks from oil and gas deposits are characterized by a liquid phase (the pore space saturation fluid) and a solid phase (the mineral skeleton), the thermal conductivity of the analyzed rock depends on the thermal conductivity of the two constituent phases.

If the two phases are oriented parallel to each other (a maximum thermal conductivity value is obtained), then:

$$k_{max} = pk_f + (1 - p)k_m \tag{9}$$

where k_{max} is the maximum conductivity of the analyzed rock, p represents the porosity of the rock, k_f tests the conductivity of the fluid phase, k_m represents the conductivity of the matrix (mineral skeleton).

If the two phases are oriented in series (which gives a minimum value of the thermal conductivity), we can write the equation of the conductivity of the deposit swarm, as:

$$\frac{1}{k_{min}} = \frac{p}{k_f} + \frac{1-p}{k_m} \tag{10}$$

For an average thermal conductivity value, the following relationship is used:

$$k = k_f^p \bullet k_m^{1-p} \tag{11}$$

Logarithmizing Eq. (11), we can obtain a linear relationship between the effective conductivity of the porous medium and the effective conductivity of the constituent fluid, namely:

$$\log k = p\ log\, k_f + (1 - p)\, log\, k_m \tag{12}$$

For rocks with low porosity and complex mineralogical composition, their conductivity can be obtained based on the relations:

$$\frac{1}{k_{min}} = \frac{V_1}{k_1} + \frac{V_2}{k_2} + \ldots + \frac{V_n}{k_n} \tag{13}$$

$$k_{max} = V_1 k_1 + V_2 k_1 + \ldots + V_n k_n \tag{14}$$

where $V_1, V_2 \ldots, V_n$, are the volumes of the mineral fractions, 1, 2 , … , n, and k_1 ,k_2, … , k_n, are the thermal conductivity of minerals.

3. Mathematical modeling

The equation that best describes thermal conductivity is given by the relationship:

$$\frac{\partial t}{\partial \tau} = a\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2}\right) \tag{15}$$

where x, y, and z are the heat dissipation directions, and t is the heat flow temperature, measured after time τ.

Sometimes it is used as a way of calculation, writing the thermal conductivity in spherical coordinates:

$$\frac{\partial t}{\partial \tau} = a\left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r} + \frac{1}{r^2}\frac{\partial^2 t}{\partial \theta^2} + \frac{\partial^2 t}{\partial z^2}\right) \tag{16}$$

And from Eq. (16) it is written:

$$\nabla^2 t = -\frac{1}{a}\frac{\partial t}{\partial \tau} = -\frac{A}{k} \tag{17}$$

Given that in the stabilized regime $\frac{\partial t}{\partial \tau} = 0$, ecuația 17 se Eq. (17) turns into Poisson's equation, namely:

$$\nabla^2 t = -\frac{A(x, y, z)}{k} \tag{18}$$

where $A(x,y,z)$ is the amount of heat that dissipates in the analyzed rock volume, and k represents the thermal conductivity of the rocks.

Oil drill	Depth	Rocks structures	Geological layers	Density g/cm^3	Porosity cm	Thermal conductivity (W/m K)
Valea Rației	2334–2335	Clay	Ponțian	2,46	4,20	0,57
Valea Rației	2530–2531	Hone	Ponțian	2,56	4,20	1,24
Valea Rației	2802–2810	Hone	Ponțian	2,80	4,40	1,37
Căldărușanca	2608–2611	Hone	Meoțian	2,10	3,92	0,79
Căldărușanca	3356–3364	Sandstone marl	Meoțian	2,28	4,05	0,42
Boldești	2942–2943,5	Hone	Helvețian	2,30	4,45	0,55
Boldești	4177–4179	Marl	Helvețian	2,52	4,20	1,27
Boldești	4468–4469	Marl	Helvețian	2,65	4,00	1,28
Izvoare	1216–1217	Clay	Eocen	2,46	4,20	1,30
Izvoare	2243–2245	Hone	Eocen	2,50	3,95	0,56
Izvoare	2841–2844	Hone	Eocen	2,60	4,05	1,01
Moreni	884–887	Hone	Helvețian	2,16	4,9	0,98
Moreni	1627–1630	Hone	Helvețian	2,54	4,5	1,08
Moreni	1730–1740	Hone	Helvețian	3,75	4	1,12

Table 1.
Analysis of the productive states of the studied deposits (oil and gas) (Moesic platform) [9, 13, 14].

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Geological structures	Thermal conductivity equation (y) as a function of density (x)	Thermal conductivity equation (y) as a function of porosity (x)	Density equation (y) as a function of porosity (x)
Valea Rației	$y = -18{,}113x^2 + 97{,}626x - 129{,}98$	$y = -68333x^2 + 55{,}417x - 110{,}97$	$y = 46569x^2 - 25{,}377x + 38{,}647$
Căldărușanca	$y = 53704x^2 - 22{,}8x + 24{,}987$	$y = -0{,}539x^2 + 34{,}402x - 42{,}826$	$y = -14{,}444x^2 + 62{,}433x - 63{,}34$
Boldești	$y = -91309x^2 + 47{,}284x - 59{,}9$	$y = -62889x^2 + 51{,}519x - 104{,}17$	$y = -11489x^2 + 44{,}011x + 0{,}4049$
Moreni	$y = -0{,}2447x^2 + 0{,}9433x - 0{,}3824$	$y = -0{,}1889x^2 + 15{,}256 - 1{,}96$	$y = 0{,}4021x^2 - 29{,}427x + 9{,}38$
Izvoare	$y = -59{,}643x^2 + 307{,}08x - 393{,}92$	$y = -40{,}476x^2 + 316{,}83 - 618{,}7$	$y = 39286x^2 - 0{,}736x + 31{,}286$

Table 2.
Equations for simulating thermal conductivity as a function of porosity and density and density as a function of porosity.

Rocks	Thermal conductivity, (determinată) λ, (W/m°C)	Density, value of literatures [14] ρ, (kg/m^3)	Thermal conductivity value of literature [14] k_r (W/m°C)	Absolute error, thermal conductivity	Density determinations, ρ, (kg/m^3)	Absolute error, density
clay	0,57	0,55	0,03508772	2,46	2,5	0,0162602
tiles	1,24	1,5	0,20,967,742	2,8	2,57	0,0821429
Sandy marl	0,42	0,66	0,57,142,857	2,28	11,455	0,4,975,877

Table 3.
Differences between the thermal conductivity of rocks drilling and density (determined values and values in the literature).

The cores (rocks) collected from the oil deposits in the Moesic platform of Romania were subjected to a heat transfer by measuring the temperature variations on each side of the rocks and crystals.

The density was achieved by weighing and measuring the volume, the determination error being 0.1% g/cm^3.

The porosity was determined by drying the cores and filling them with helium (according to Boyle-Marriote's law pV = const.) in a controlled closed tank.

The data measured in the laboratory are shown in **Tables 1** and **2**.

In order to model the geothermal structure of the analyzed deposit, we created numerical equations that best describe the variation of thermal conductivity depending on the density and porosity of the constituent rocks.

The equation form is:

$$y = ax^2 + bx + c \tag{19}$$

where a, b, and c are experimentally determined coefficients.

The absolute error of the determined values are compared to the values from the specialized literature we determined with the relation (**Table 3**):

$$AE = \frac{x_{models} - x_{international\ papers}}{x_{models}} \tag{20}$$

The error is a maximum of 0,5 in conductivity, in the case of shale clay, due to the fact that it was not pure.

The density errors are large because the chosen cores were not pure, being impure with other materials.

4. Conclusion

Research on the fluidity of oil and gas deposits also led to the understanding of the role of thermal conductivity in studying the phenomena of hydrocarbon migration and their formation.

Also, the use of thermal conductivity in determining the secondary (injection of gases and hot water into the deposit) and tertiary (underground combustion, steam injection into the deposit) recovery mode created the need for the experimental determination of this property of the constituent rocks.

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Tikhomirov scientifically established based on the determination of the thermal conductivity of the rocks constituting the oil and gas deposits that the calculation relationship of this property (thermal conductivity) is [1, 14]:

$$k_{sat,T} = 26{,}31e^{0{,}6\ \rho+0{,}6\ S_A}T^{-0{,}55} \tag{21}$$

where $k_{sat,T}$ is the thermal conductivity of the rock saturated with the constituent fluids, ρ is density (g/cm^3), T is temperature of determination (°C).

The author estimates an error in the thermal conductivity determination of 16%.

Cermak also used a relationship to determine conductivity as a function of density (for calcareous rocks) [1, 14]:

$$k_{sat} = 2{,}15 \bullet 10^{-3}\rho - 3{,}16 \tag{22}$$

For carbonate rocks, the above relation can be written [1, 14]:

$$k_{sat} = 4{,}18 \bullet 10^{-3}\rho - 7{,}97 \tag{23}$$

In relations (22) and (23) the density is expressed in kg/m^3.

But even these equations give errors of over 15%.

But our calculation method, namely the statistical determination of thermal conductivity as a function of porosity and density, indicated a very small error (maximum 0.5%).

In this chapter, the conductivity of fluid-saturated rocks can also be determined.

As can be seen, the data in the literature are very close to the determined values.

Also in this book chapter, we managed to model the thermal conductivity depending on the density and porosity of the rocks.

The equations that best describe this behavior are polynomial, the values of the coefficients being a function of the porosity and density of the rocks.

Author details

Chis Timur[1]*, Jugastreanu Cristina[2], Tabatabai Seyed Mehdi[2] and Renata Radulescu[2]

1 Ovidius University Constanta, Romania

2 Oil-Gas University, Ploiesti, Romania

*Address all correspondence to: tchis@univ-ovidius.ro

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