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Heat capacity of two-phase systems according to the law of additivity

Wydajność cieplna układów dwufazowych na podstawie prawa addytywności

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ABSTRACT: Practice shows that the temperature around drilling and production wells is of great interest in terms of design choices and preventing the precipitation of heavy fractions (paraffins, resins, asphaltenes). A literature analysis has demonstrated that the temperature of the elements of drilling and production wells can be determined with sufficient reliability using the method of successive changes in the stationary state. To select downhole equipment, both during drilling and operation, it is necessary to determine the temperature values for the wells. The performed calculations indicate that the change in the temperature of hydrocarbons along the wellbore during flow operation is considered in three cases of annulus filling. To refine the temperature calculations, they must be conducted step by step, dividing the length of the lift into specific intervals. Similar temperature calculations are also carried out for injection wells when hot water is injected into the reservoir. In such cases, it is important to maintain the temperature of the injected water above the formation temperature. The temperature of the water injected into the reservoir from the wellhead to the bottom of the well is determined by solving the equations of thermodynamics and heat transfer jointly. Literature analysis shows that, to calculate the temperature of produced or injected water, it is necessary to know the thermophysical properties of well production, reservoir fluids, cement stone, and surrounding rocks. In a particular case, a water-gas-oil mixture moves through a production well, with the concentration of its phases and components changing as it moves upwards to the wellhead. A similar mixture system is also present in the annular space between the pipe strings and within the pores of the rock.

Key words: two-phase systems, additivity, mixture, conductivity coefficient, thermophysical properties.

STRESZCZENIE: Praktyka pokazuje, że temperatura wokół otworów wiertniczych i eksploatacyjnych jest bardzo istotna z punktu widzenia założeń konstrukcyjnych i zapobiegania wytrącaniu się frakcji ciężkich (parafiny, żywice, asfalteny). Analiza literatury wykazała, że temperatura komponentów otworów wiertniczych i eksploatacyjnych może zostać wystarczająco wiarygodnie wyznaczona metodą kolejnych zmian w stanie stacjonarnym. W celu doboru urządzeń wiertniczych, zarówno podczas wiercenia, jak i eksploatacji, konieczne jest określenie wartości temperatury dla odwiertów. Przeprowadzone obliczenia wskazują, że zmiana temperatury węglowodorów wzdłuż odwiertu podczas przepływu jest uwzględniana w trzech przypadkach wypełnienia przestrzeni pierścieniowej. W celu dokładniejszego przeprowadzenia obliczeń temperatury, należy przeprowadzić je krok po kroku, dzieląc odcinek podnoszenia na określone przedziały. Podobne obliczenia temperatury są również przeprowadzane dla odwiertów zatłaczających, gdy gorąca woda jest wtryskiwana do zbiornika. W takich przypadkach ważne jest utrzymanie temperatury zatłaczanej wody powyżej temperatury formacji. Temperatura wody zatłaczanej do zbiornika od głowicy odwiertu do dna odwiertu jest określana poprzez jednoczesne rozwiązanie równań termodynamiki i wymiany ciepła. Analiza literatury wykazała, że aby obliczyć temperaturę produkowanej lub zatłaczanej wody, konieczne jest poznanie właściwości termofizycznych produkcji odwiertu, płynów złożowych, kamienia cementowego i otaczających skał. W szczególnych przypadkach mieszanina wody, gazu i ropy naftowej przemieszcza się przez odwiert wydobywczy, a stężenie jej faz i składników zmienia się w miarę przemieszczania się w górę do głowicy odwiertu. Podobny układ mieszanin jest również obecny w przestrzeni pierścieniowej między przewodami rurowymi i w porach skał.

Słowa kluczowe: układy dwufazowe, addytywność, mieszanina, współczynnik przewodnictwa, właściwości termofizyczne.

Introduction

Numerous laboratory and field studies show that at all stages of the oil and gas industry – from exploration to hydrocarbon processing – there is a need to solve numerous problems associated with the processes of heat distribution and transfer from the well to the formation and vice versa.

During the drilling and exploitation of oil and gas deposits, the natural temperature distribution in the subsoil and the interpretation of geophysical well surveys occupy a special

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place. Different values of the temperature gradient along the depth of the well highlight the varying ability of the formation rocks to transfer heat.

In oil field operations, the sedimentation of heavy components such as paraffin, asphaltene, and resin can occur, primarily due to temperature changes in the hydrocarbon during filtration within the formation and as they move upward in the well. This underscores the importance of selecting an appropriate well design. When choosing surface and underground equipment or determining the well design, it is crucial to account for temperature changes in the lifting pipes. Temperature calculations for the movement of oil through lifting pipes from the bottom to the wellhead are based on the joint solution of thermodynamics and heat transfer equations under variable temperature conditions, with or without consideration of internal sources.

The temperature field in the well and around the well bottom is largely determined by thermophysical properties of the formation fluid and surrounding rocks (Vargaftik, 1972; Bulakh and Bulakh, 2018; Grigoriyev, 2019).

Practice shows that temperature fields in a well are often determined by the thermophysical properties of the formation fluid, surrounding layers, and rocks. Additionally, the process of extracting reservoir oil, gas, or condensate (Somerton, 1992; Middleton, 1994; McKenna and Sharp, 2008) at the wellhead is accompanied by changes in pressure and temperature, leading to variations in the concentrations of its individual components.

Numerous analyses (Somerton, 1992; Middleton, 1994) have shown thermal calculations require initial data and calculation methods.

The reliability of these calculations depends not only on a sound methodological support but also on the accuracy of determining the parameters of thermophysical properties (Middleton, 1994; Aliyev, 2023; Dadash-zade and Aliyev, 2023). Notably, the error in determining thermophysical properties must be smaller than the errors allowed when deriving the equation for calculating thermal fields and heat transfer.

Thermophysical properties of formation fluids are determined experimentally and analytically. Experimental data, however, are valid only for the specific parameters studied. Generalization of and adaptation of experimental data to other parameters and objects is impossible without application of analytical methods.

This paper proposes an analytical method to predict the thermophysical properties of formation fluids with an error comparable to that of experimental methods.

The process of hydrocarbon production is accompanied by changes in pressure and temperature, leading to alteration in the concentrations of their constituent components (Kuptsov, 2006; Dunyashkin, 2005).

Scientific background

Thermal calculations require initial parameters and calculation methods for drilling, production, and transportation. The reliability of these calculations, in addition to proper methodological and scientific support, depends on the accuracy of determining the thermophysical properties – thermal conductivity coefficients and heat capacity – of both the entire system and its individual components (Norden and Forster, 2006).

Purpose of work

As is known, to experimentally determine the thermophysical properties of a formation fluid moving within a well, it is necessary to account for changes in thermobaric parameters, composition, and component concentrations, which is a complex process. Experimentally measuring the thermophysical properties of rocks and individual layers is also challenging.

It is more economical to determine the thermophysical properties of formation fluids and rocks using analytical methods. This approach to determining the parameters of the thermophysical properties of inhomogeneous substances is based on models of heat transfer in two-phase or multiphase, multicomponent mixtures. In this work, it is proposed to represent any multicomponent system by successive actions in the form of a simple two-phase or two-component mixture.

Problem statement and solution

Practice shows that the parameters of mixtures determined by mass can be calculated using the additivity rule (Yashchenko and Polishchuk, 2019; Aliyev, 2023; Dadash-zade and Aliyev, 2023). Accordingly, the density and heat capacity of mixtures can be determined with sufficient accuracy. In this case, these indicators can be determined based on the concentration and parameters of the components or phases.

Considering the above, let us determine the main characteristics of the mixture.

It is known that the concentration of the mixture components is the key parameter. In this case, the mass concentration is determined as:

$$m = \frac{M_i}{M} = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{1}$$

where: M_i and M are the masses of the i-th component and the entire mixture.

Volume concentration for liquid and gas:

$$v_i = \frac{V_i}{V} = \frac{V_i}{\sum_{i=1}^{n} V_i} \tag{2}$$

where: V_i and V are the masses of the i-th component (phase) and the entire mixture, respectively.

Molar mass of mixture:

$$n_m = \sum_{i=1}^{n} \varepsilon_i n_i = \frac{1}{\sum_{i=1}^{n} \frac{m_i}{n_i}} \tag{3}$$

where: n_i is the molar mass of the i-th component of the mixture.

Let us determine the density of a mixture consisting of individual components or phases:

$$\rho = \sum_{i=1}^{n} v_i \rho_i = \frac{1}{\sum_{i=1}^{n} \frac{m_i}{\rho_i}} \tag{4}$$

where: ρ_i is the density of the i-th component or phase.

Specific mass isobaric heat capacity of the mixture can be determined as:

$$C_p = \sum_{i=1}^{n} m_i C_{pi} \tag{5}$$

where is C_{pi} the specific mass isobaric heat capacity of the i-th component or phase of the mixture.

To study the mixture in more detail, it is necessary to know the thermal conductivity coefficient (Zhao et al., 2013; Sunday et al., 2022).This parameter is not an additive function; its numerical value depends on the concentrations, thermal conductivity coefficients of individual components or phases that make up the mixture, and the direction of heat flow.

Studies have shown that the thermal conductivity of a mixture is not an additive function. Instead, it depends on various parameters, including concentrations, values of thermal conductivity coefficients of components or phases, as well as the structure of the mixture and the direction of heat flow.

In the literature (Baibakov et al., 2011), mixtures are classified as equilibrium or non-equilibrium (isolated) components or phases based on their structure. Laboratory experiments reveal that for mixtures with non-equilibrium components, a base and an external phase of the mixture, and isolated inclusions or a dispersed phase are distinguished. If the mixture consists of equally directed components, such division does not play a significant role. In this case, the numerical value of the thermal conductivity coefficient of the mixture will be in the interval between the minimum and maximum values, depending on the heat flow direction (Hasan et al., 1998).

The minimum value of the thermal conductivity coefficient perpendicular to heat flow:

$$\lambda_i = \frac{1}{\sum_{i=1}^{n} \frac{v_i}{\lambda_i}} \tag{6}$$

And the maximum value is parallel to heat flow:

$$\lambda_i = \sum_{i=1}^{n} v_i \lambda_i \tag{7}$$

Arithmetic mean:

$$\lambda_{cp} = \frac{\lambda_{i\max} + \lambda_{i\min}}{2} \tag{8}$$

In practical conditions it is possible to determine the value using the arithmetic mean.

In many cases, determining the thermal conductivity coefficient of individual components (oils, condensate) is necessary. The literature contains extensive experimental data on the dependence of the thermal conductivity coefficient on the physical properties of the component. Our analysis indicates that the most reliable correlation is between the thermal conductivity coefficient and oil density. Figure 1 shows this dependence. As can be seen from the figure, knowing the numerical value of oil density allows for the determination of its thermal conductivity coefficient.

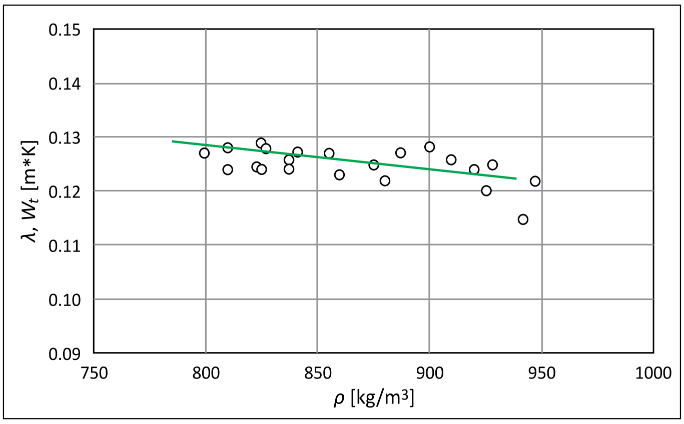

Figure 1. Dependence of the thermal conductivity coefficient on oil density

Rysunek 1. Zależność współczynnika przewodności cieplnej od gęstości ropy

Discussion

The most challenging objects for studying thermophysical properties in the oil and gas industry are rocks whose pores contain hydrocarbons. The thermophysical characteristics of rocks have been studied for a long time, resulting in a wealth of theoretical and experimental data for specific rocks from individual deposits. Analysis shows that the study of various parameters, such as density, porosity, temperature, pressure, and pore fluid saturation, significantly depends on the thermophysical properties of specific samples of the component system. In this context, the rock can be represented as a two-component system, where the first element is the solid frame (rock matrix) of the rock, and the second is the formation hydrocarbon.

The studies conducted show that, depending on the stage of the technological process of development, production and transportation, the object under consideration can be formation fluid, rock, formation and degassed oil, gas, formation water, gas-oil and water-gas-oil mixture. For processes associated with heat exchange at the solid-oil, solid-gas interface, this work derived calculation formulas with a minimum error margin of 3–5%, which is an acceptable level of accuracy for determining thermophysical properties.

It should be noted that the experimental methods for determining thermophysical properties are reliable only for specific oils, gases, rocks and the conditions of their coverage and should serve as reference tests (Somerton, 1992; Middleton, 1994). The high cost of these experiments and the reliability of application of the obtained results, even for similar systems, suggest the widespread use of analytical methods for predicting the parameters of the thermophysical properties of fluids and formations.

In this work, the materials make it possible to present a methodology for predicting the thermophysical properties of formation fluids and rocks of oil and gas fields. The study of these parameters remains an urgent task for engineers.

Conclusion

1. The analysis showed that with known values of the parameters of the thermophysical properties of components or phases and their concentrations, it is possible to estimate the density, heat capacity, and knowing the structure of the mixture and the thermal conductivity of any reservoir system.
2. In practical conditions, predicting thermophysical properties for complex reservoir systems requires first breaking the system into the simplest components. By combining these components in pairs and studying their properties, it is possible to gradually move on to the complex system under consideration.

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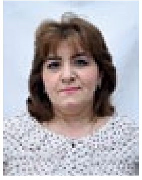

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