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The method for calculating technological indicators in the development of gas wells while considering the thermobaric and thermodynamic conditions within the "reservoir-well" system

Metoda obliczania wskaźników technologicznych eksploatacji odwiertów gazowych z uwzględnieniem warunków termobarycznych i termodynamicznych w układzie „złoże-odwiert"

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ABSTRACT: Considering the substantial prevalence of gas fields in the pool of developed fields, their development requires specialized approaches with the primary objective of optimizing the production process. The effectiveness of gas field development hinges on achieving the highest possible gas recovery factor. Achieving a high limit of the ultimate return of gas fields relies on decisions that vary depending on the precision of design estimates carried out at different stages of development and their timely execution. The accuracy of such estimates is, if possible, directly contingent on the thorough consideration of geological, technical, and technological factors when formulating methods for determining field development and operation indicators. Given the above considerations, this article proposes a methodology for determining the technological indicators of gas reservoir development, which enables to anticipate changes in reservoir pressure, temperature, and porosity of the gas reservoir, while accounting for the gas-dynamic interplay within the "reservoir-well" system in the depletion phase. The developed approach makes it possible to reliably ascertain reservoir development metrics by factoring in well conditions, temperature distribution within the reservoir, and reservoir deformation. In addition, it facilitates the necessary assessment for determining optimal well operations in light of reservoir conditions.

Key words: gas reservoir, porosity, pressure, temperature, flow rate, gas riser, thermobaric reservoir condition, reservoir deformation.

STRESZCZENIE: Biorąc pod uwagę duży udział złóż gazu w eksploatowanych zasobach węglowodorów, ich zagospodarowanie wymaga zastosowania specjalistycznego podejścia, który ma przede wszystkim umożliwić jak najefektywniejsze przeprowadzenie tego procesu. Efektywna realizacja procesu udostępnienia złóż gazu polega przede wszystkim na osiągnięciu maksymalnego współczynnika wydobycia gazu. Podejmowanie decyzji w zależności od stopnia dokładności szacunków projektowych przeprowadzanych na dowolnym etapie zagospodarowania złoża i ich terminowe wdrażanie umożliwia osiągnięcie wysokich wartości wydobycia gazu. Z kolei zapewnienie dokładności takich szacunków, o ile jest to możliwe, zależy bezpośrednio od tego, czy przy tworzeniu odpowiednich metod określania wskaźników zagospodarowania i eksploatacji złoża uwzględnione zostaną w pełni czynniki geologiczne i techniczno-technologiczne. Biorąc pod uwagę powyższe, w artykule zaproponowano metodę określania technologicznych wskaźników zagospodarowania złóż gazu, która pozwala przewidywać zmiany ciśnienia złożowego, temperatury i porowatości w obrębie złoża gazu, biorąc pod uwagę zależność gazowo-dynamiczną układu „złoże-odwiert" w trybie sczerpywania. Opracowana technika umożliwia wiarygodne określenie wskaźników zagospodarowania złoża, z uwzględnieniem warunków panujących w odwiertach, rozkładu temperatury w złożu i deformacji złoża. Ponadto możliwe jest przeprowadzenie niezbędnej oceny w celu określenia optymalnych reżimów eksploatacji odwiertów, biorąc pod uwagę warunki panujące w złożu.

Słowa kluczowe: złoże gazu, porowatość, ciśnienie, temperatura, natężenie przepływu, rura wznośna gazu, warunki termobaryczne złoża, deformacja złoża

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Introduction

Forecasting technological indicators for the development of gas fields is an important task in advancing the design process across its various stages.

The technological indicators of the development process encompass aspects such as the annual volumes of hydrocarbon and water extraction, the injection of working agents, drilling lengths, the commissioning and decommissioning of wells of all categories, the number of operational wells, the average flow rates of production wells, and the injectivity of injection wells, characterizing the development of the field (operational facility). When the technological indicators align with the design parameters, it indicates a high level of reliability in the calculated values within the design process and the effectiveness of the methods used to influence hydrocarbon deposits.

In view of the fact that the process of field development is influenced by a complex interplay of geological and physical factors, the basic task of predicting development indicators is to create reliable calculation methods for determining technical and technological indicators that comprehensively account for the impact of these factors. With the increasing importance of deep-seated gas fields, these issues have acquired particular relevance and attracted the attention of many scientists and experts, as evidenced by a substantial body of published research dedicated to studying these challanges. For example, mainly for the case of deep-seated deposits, a publication by Mirzajanzade et al. (2003) generalizes the problems related to various gas production technologies, providing practical application of the results from corresponding theoretical studies. This work particularly focuses on the features of formulating and solving problems associated with natural gas production under different technological conditions. Zakirov (2001) studied the problems of forecasting, analysis, and regulation of oil and gas field development in three-dimensional contexts. Given that deep-seated gas fields often exhibit complex reservoir structures and petrophysical characteristics, the influence of these geological and physical attributes on the determined field development indicators is further complicated by the impact of various thermodynamic conditions both within the wellbore and the reservoir on the properties hydrocarbon gas (Zakirov et al., 1988).

The papers presented by Yesaulov and Trufanov (2016), Gasumov (2022), and Khandzel et al. (2022), respectively, show the role of factor analysis in the "reservoir-well-gas pipeline" system, the need to consider the mutual influence of reservoir and well conditions when analyzing gas well operations and designing the development of specific oil and gas condensate field, as well as the basic principles of systems analysis in the design and management of gas field development. The publications by Gasumov et al. (2021), Tolpayev and Akhmedov (2021), respectively, establish the theoretical foundations for devising geological and technical strategies for gas wells, as well as constructing mathematical models for predicting gas well productivity.

The above substantiates the need to create methods for calculating development indicators in gas fields that take into account the complex gas-dynamic situation in the "reservoir-well" system, primarily associated with changes in the actual physical properties of the gas and the capacity and energy characteristics of the reservoir. These methodologies facilitate the prediction of gas field development indicators by accounting for the real thermobaric and thermodynamic conditions within the reservoir and well. Moreover, in cases where the potential for certain types of geological and technological complications arises, these methods enable to make the necessary evaluation calculations to determine optimal well operation modes.

Considering the preceding discussions, this article investigates the issue of ascertaining the technological parameters for the development of gas reservoirs, taking into account the gas-dynamic interactions within the "reservoir-well" system, complicated by the influence of thermobaric and thermodynamic conditions both within the reservoir and the well.

Methods and discussion

We assume that the circular gas deposit is drained by the central well in the depletion mode. The rocks within the formation are subjected to non-linear elastic deformation. The reservoir development process is affected by the thermobaric condition, which characterizes the combined impact of changes in reservoir pressure and temperature (Kuliyev and Kazymov, 2009; Kochina et al., 2017; Kazymov and Nasirova, 2021). These papers present the characteristics of elastic and inelastic deformations as well as temperature effects in the context of oil and gas field development. They also explore the possibilities of taking these phenomena into account in the analysis and design of field development, as well as offer a method for choosing the optimal operational mode for a gas well, considering the deformation of rocks (Jalalov and Feyzullayev, 2015; Kazymov and Kerimova 2020; Poryadin and Borovsky, 2020).

In the case where rocks exhibit nonlinear elastic deformation, the formation porosity (ϕ), taking into account the influence of thermobaric conditions, can be accomplished following a specific rule (Zakirov et al., 1988).

$$\phi = \phi_0 e^{\beta_r (p-p_0)-\beta_T (T-T_0)} \tag{1}$$

where:

p – formation pressure,

T – reservoir temperature,

ϕ_0, T_0 and p_0 – respectively, the initial values of porosity, permeability, temperature, and reservoir pressure,
β_r – coefficient of elastic compressibility of the reservoir,
β_T – coefficient of thermal expansion of the formation.

Changes in the formation temperature depending on the pressure can be expressed in the following form, adopted by Chekalyuk (1965) and Karachinsky (1975), i.e. considers the change in reservoir temperature as a result of the slow flow of gas influenced by reservoir pressure without heat exchange with the environment (adiabatic conditions).

$$T = T_w + \varepsilon(p - p_w) \tag{2}$$

where:
T_w – bottom hole temperature,
p_w – bottom hole pressure,
ε – Joule-Thomson coefficient.

During the operation of a gas deposit with a central well, it is assumed that the change in reservoir pressure in all its sections is almost equal to some volume-weighted average pressure (p_{avg}), which can be determined from the gas balance equations (Lapuk, 2002). According to this assumption, assuming that $p \approx p_{avg}$, reservoir pressure, considering the change in reservoir temperature, we will determine from the following balance equation that relates the volume of gas production q_ε to the energy potential of the reservoir (Lapuk, 2002):

$$q_g = -\frac{\Omega}{p_{at}}\frac{d}{dt}\left(\frac{\phi p}{Z(p)}\frac{273}{293+T}\right) \tag{3}$$

where:
$Z(p)$ – is the coefficient of gas super compressibility,
Ω – deposit volume,
p_{at} – atmosphere pressure.

We know that the changes in gas reservoir development indicators should be directly determined based on the operational parameters of wells, such as wellhead and bottomhole pressures and temperatures, hydraulic losses, gas compressibility, etc. In this regard, even though equations (1)–(3) form a closed system of equations for determining the main natural and technological characteristics of reservoir development, the simultaneous solution of this system necessitates the specification of changes in bottomhole pressures and temperatures (p_w and T_w). These values can be determined by considering the basic equations for calculating the lift, and the effects on them of various other downhole performance characteristics. The calculation of the gas lift, according to Kerimova (2021), Arbuzov and Kurganova (2015), Gunkina and Fedorova (2015), is carried out according to the following formula, which relates changes in the gas flow rate of a gas well (in thousand m^3/day) with the given values of the internal diameter of the lift (d), bottom hole pressure (p_w) and wellhead pressure (p_{wh}), [Pa]:

$$Q_g = \frac{d}{1.17\cdot 10^{-6} Z_{avg} T_{avg}}\sqrt{\frac{(p_w^2 - p_{wh}^2 e^{2S})d}{(e^{2S}-1)\lambda}} \tag{4}$$

where:
λ – hydraulic losses of gas in the lift,
Z_{avg} – average coefficient of gas super compressibility in the well,
T_{avg} – average temperature in the well [K]:

$$T_{avg} = \frac{T_w - T_{wh}}{\ln\left(T_w / T_{wh}\right)} \tag{5}$$

T_w – gas temperature at the bottom of the well [K],
T_{wh} – gas temperature at the wellhead [K],
S – exponent:

$$S = 0.03415\frac{\bar{\rho} L}{T_{avg} Z_{avg}} \tag{6}$$

$\bar{\rho}$ – relative density of gas in air,
L – the depth of the gas lift.

The use of formula (4) helps to determine one of the operational characteristics d, p_w, p_{wh}, T_w, T_{wh} for given values of well flow rates. Since the values of change p_{wh} and T_{wh} can be determined at the wellhead, then for a given value of the diameter of the lift, this formula can be used to determine either p_w – bottom hole pressure, or T_w – bottom hole temperature.

Through a joint study of equations (1)–(3), the following objective was derived: to ascertain the changes in reservoir pressure, taking into account changes in geological and physical attributes of the reservoir system such as porosity and reservoir temperature:

$$\frac{dp}{dt} = -\frac{Q_g + F_1(\phi, p)}{F_2(\phi, p)} \qquad p(0) = p_0 \tag{7}$$

where:

$$F_1(\phi, p) = \\ = \left(\frac{\Omega}{p_{at}}\frac{\phi p}{Z(p)}\frac{273\beta_T}{293+T} - \frac{\Omega}{p_{at}}\frac{\phi p}{Z(p)}\frac{273}{(293+T)^2}\right)\cdot \\ \cdot\left(\frac{dT_w}{dt} - \varepsilon\frac{dp_w}{dt}\right) \tag{8}$$

$$F_2(m, p) = \\ = \frac{\Omega}{p_{at}}\frac{\phi}{Z(p)}\frac{273}{293+T} + \frac{\Omega\phi}{p_{at}}\left[\frac{p}{Z(p)}\right]'\frac{273}{293+T} + \\ + \frac{\Omega}{p_{at}}\frac{p}{Z(p)}\frac{273}{293+T}\left(\phi\beta_r + \varepsilon\phi\beta_T\right) - \\ - \frac{\Omega}{p_{at}}\frac{\phi p}{Z(p)}\frac{273}{(293+T)^2}\varepsilon \tag{9}$$

$$T = T_w + \varepsilon (p - p_w) \qquad (10)$$

$$\phi = \phi_0 e^{\beta_r (p - p_0) - \beta_T [\varepsilon (p - p_w) - (T_0 - T_w)]} \qquad (11)$$

Thus, a method for determining the technological indicators of well operation in the development of a gas reservoir is introduced, which considers the deformation of rocks and temperature fluctuations within the reservoir.

Based on the model, numerical calculations were carried out with the following reservoir and well data:
$p_0 = 40$ MPa; $T_0 = 397$ K; $\phi_0 = 0.2$; $r_w = 0.1$ m; $r_c = 1000$ m; $h = 20$ m; $p_{at} = 0.1$ MPa; $\lambda = 0.014$; $S = 0.371$; $Z_{avg} = 0.916$; $T_w = 337$ K; $T_{wh} = 304$ K; $p_w = 20$ MPa; $p_{wh} = 10$ MPa; $L = 3000$ m; $\bar{p} = 1.06$; $Q_g = 1.5 \cdot 10^6, 3 \cdot 10^6$ m^3/day; $\beta_r = 2.5 \cdot 10^{-3}$ MPa^{-1}; $\varepsilon = 3$ K/MPa; $\beta_T = 0.0002$ 1/K; $Z(p) = 1 - 0.1162 \cdot 10^{-1} \cdot p + 0.3744 \cdot 10^{-3} \cdot p^2 - 0.2965 \cdot 10^{-6} \cdot p^3 - 0.1975 \cdot 10^{-7} \cdot p^4$

Some calculation results are shown in Figures 1–3. Figures 1 and 2 illustrate changes in reservoir pressure as a function of time for cases with and without accounting for reservoir deformation and temperature fluctuations in the reservoir, respectively, in the cases of $Q_g = 1.5 \cdot 10^6$ m^3/day and $Q_g = 3 \cdot 10^6$ m^3/day.

Figures 1 and 3 show that the reservoir pressure for both scenarios with specified gas well flow rates, considering the formation deformation and temperature fluctuations within the reservoir results in a more rapid decline compared to not accounting for these factors. Moreover, the difference in the rate of reservoir pressure decrease in these circumstances becomes increasingly pronounced as the reservoir development progresses over time. For example, for a lower well flow rate by the end of reservoir development, the reservoir pressure values in these instances may differ by up to 7.5%. This fact indicates the need to take into account the noted thermodynamic and thermobaric conditions of the formation in gas-dynamic calculations to determine the indicators of its development. This is also evidenced by the results of determining the change in the formation porosity and temperature in the formation over time, illustrated in Figures 3 and 4.

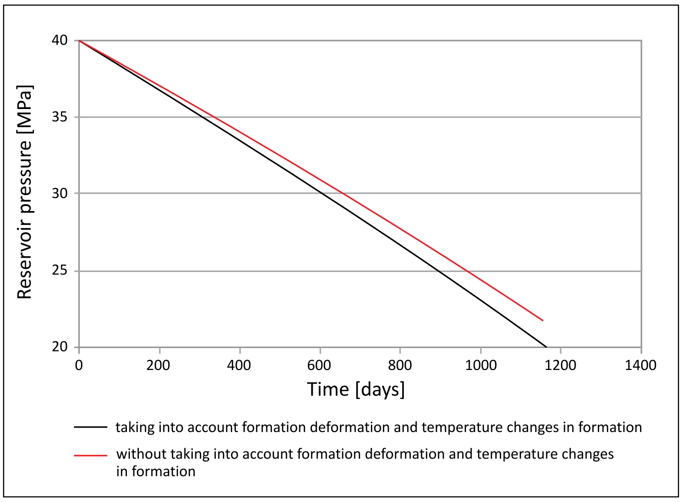

Figure 1. Change in reservoir pressure depending on time in the case of $Q_g = 1.5 \cdot 10^6$ m^3/day

Rysunek 1. Zmiana ciśnienia złożowego w czasie dla $Q_g = 1{,}5 \cdot 10^6$ m^3/dzień

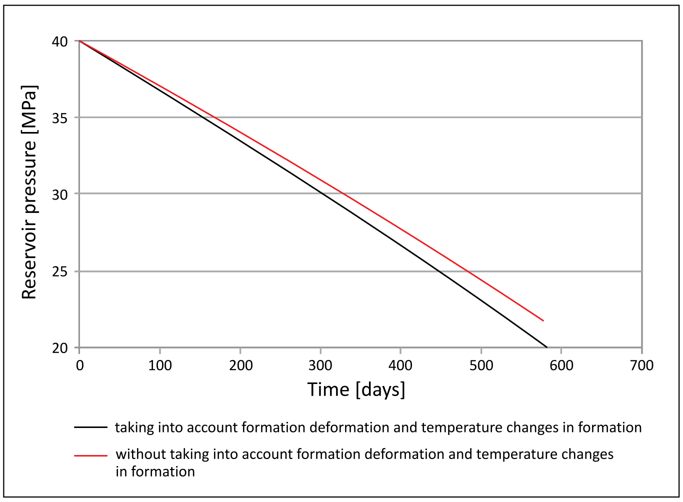

Figure 2. Change in reservoir pressure depending on time in the case of $Q_g = 3 \cdot 10^6$ m^3/day

Rysunek 2. Zmiana ciśnienia złożowego w czasie dla $Q_g = 3 \cdot 10^6$ m^3/dzień

The time curves of reservoir porosity and reservoir temperature presented in Figures 3 and 4 when considering reservoir deformation and temperature variations in the reservoir indicate that under these circumstances, both reservoir porosity and reservoir temperature may exhibit a continuous decline, starting from their initial reservoir values. Furthermore, the increase in the well flow rate by a factor of two reduces the determined values of the development indicators in time by a factor of two.

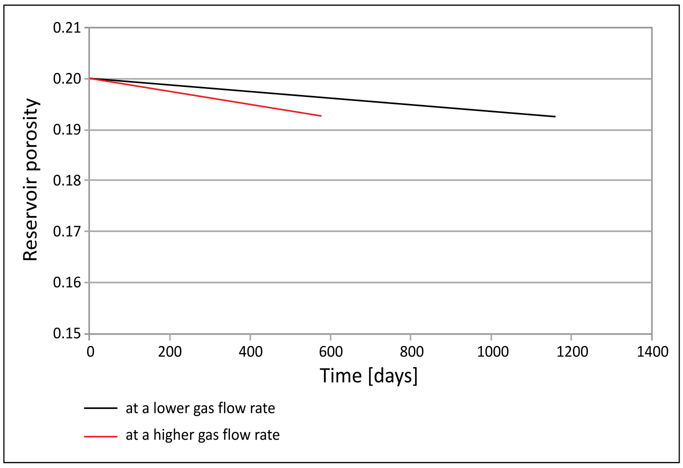

Figure 3. Change in formation porosity depending on time in cases of $Q_g = 1.5 \cdot 10^6$ m^3/day

Rysunek 3. Zmiana porowatości formacji w czasie dla $Q_g = 1{,}5 \cdot 10^6$ m^3/dzień

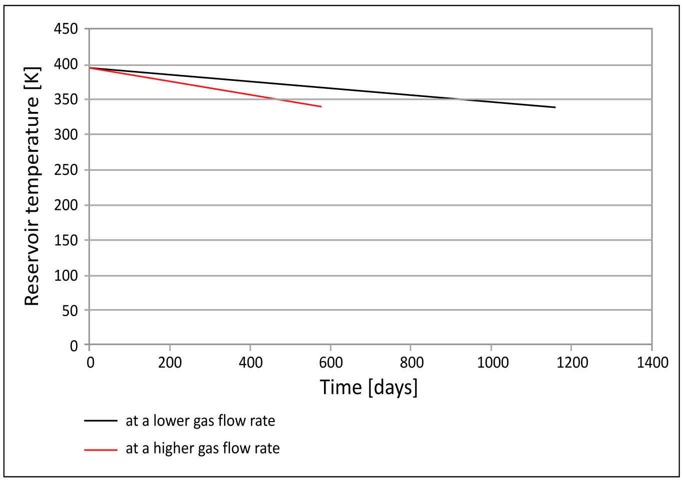

Figure 4. Formation temperature change depending on time in cases of $Q_g = 1.5 \cdot 10^6$ m^3/day and $Q_g = 3.0 \cdot 10^6$ m^3/day

Rysunek 4. Zmiana temperatury formacji w czasie dla $Q_g = 1{,}5 \cdot 10^6$ m^3/dzień i $Q_g = 3{,}0 \cdot 10^6$ m^3/dzień

The well production rate is influenced by several factors, including the permeability and thickness of the productive horizon, its supply conditions, distribution, and relationship with other horizons, the presence of pressure and other factors, as well as by the operating conditions of the productive horizon, the degree of its opening, the lowering of oil or gas levels during pumping, and other elements. In this context, high-rate and low-rate wells should be understood.

Due to the fact that model constraints can be specified:

- the model does not account for thermodynamic phenomena, such as adiabatic gas expansion, thermal conductivity of the rock matrix, etc.;
- obtaining information regarding changes of bottomhole pressures and temperatures over time is, from a practical standpoint, contingent on conducting specialized studies (a comparison of the proposed model was not performed).

Conclusions

1. Thus, a method for determining the technological indicators of well operation in the development of a gas reservoir is introduced, which considers the thermobaric and thermodynamic conditions in the reservoir and well.
2. The proposed method enables to anticipate changes in reservoir pressure, temperature, and porosity of a gas reservoir, while accounting for the gas-dynamic interplay within the "reservoir-well" system during the development of a gas reservoir in the depletion phase. It has been established that neglecting to take into account the influence of thermobaric conditions within the reservoir can lead to significant errors when determining the development indicators of a gas reservoir.
3. The proposed methodology can also be usefully applied in determining the optimal reservoir operation modes that require access to data regarding changes in the values of reservoir development indicators over time.

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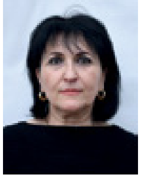

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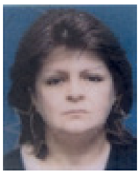

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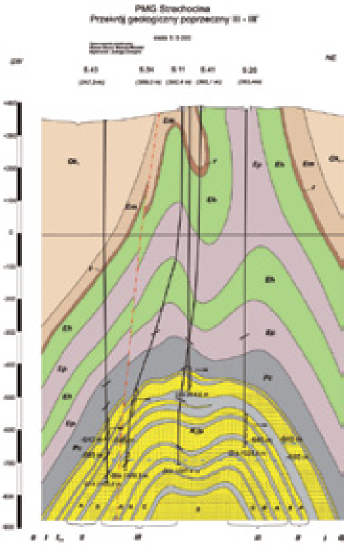
OFERTA BADAWCZA ZAKŁADU
PODZIEMNEGO MAGAZYNOWANIA GAZU

- analiza struktur geologicznych złóż gazu ziemnego, ropy naftowej oraz obiektów zawodnionych, pod kątem możliwości ich przekształcenia w PMG;
- szczegółowa analiza warunków geologiczno-złożowych, ocena dotychczasowej eksploatacji złoża, warunków hydrodynamicznych, zdolności wydobywczych odwiertów;
- ocena stanu technicznego istniejącej infrastruktury w aspekcie jej wykorzystania w pracy PMG;
- wykonywanie cyfrowych modeli geologicznych PMG, złóż gazu ziemnego i ropy naftowej;
- wykonywanie projektów budowy PMG;
- analiza dotychczasowej pracy istniejących PMG w celu optymalizacji parametrów dalszej eksploatacji magazynów na bazie symulacji komputerowej;
- opracowanie projektów prac geologicznych, dotyczących poszukiwania i rozpoznawania złóż gazu ziemnego i ropy naftowej;
- opracowanie dokumentacji geologicznych złóż ropy naftowej i gazu ziemnego;
- opracowanie programu optymalnej eksploatacji złoża, wydajności poszczególnych odwiertów, tempa sczerpywania itp.



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