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Investigation of Rate-Decline Analysis for Assessment of Recoverable Resources of Polish Shale Gas Formations

The paper presents investigations of rate-decline analysis and its feasibility in the assessment of gas resources discovered in Polish shale formations. The investigation uses both one- and two-phase simulation models constructed and calibrated for typical shale formations discovered and tested by Polish operators. Various types of rate-decline curves are investigated. Expected uncertainties of gas resources estimated by the rate-decline curves are found depending on the available production data period for various geological parameters and gas production mechanisms. General conclusions are drawn from the results of the analysis for the practical usage of rate decline curves in the process of the resource estimates of Polish shale gas formations.

Key words: shale formations, rate-decline curves, reservoir simulation models, recoverable resources.

Analiza możliwości wykorzystania krzywych spadku wydajności do oceny wydobywalnych zasobów gazu z krajowych struktur łupkowych

W pracy przedstawiono analizę stosowalności metod krzywych spadku wydajności do oceny wydobywalnych zasobów krajowych struktur łupkowych. Analizę tą przedstawiono z wykorzystaniem jedno- i dwufazowych symulacyjnych modeli tych struktur skonstruowanych i skalibrowanych w oparciu o dane geologiczne i testowe z odwiertów nawierconych ostatnio na koncesjach operatorów krajowych. Przedstawiono podstawowe typy krzywych spadku wydajności. Oszacowano możliwe błędy określenia zasobów zależnie od długości okresu eksploatacji i dopasowania przebiegu wydobycia oraz podstawowych parametrów geologicznych. Sformułowano ogólne wnioski o praktycznym znaczeniu dla doboru metodyki szacowania zasobów gazu w krajowych strukturach łupkowych.

Słowa kluczowe: struktury łupkowe, krzywe spadku wydajności, symulacyjne modele złożowe, zasoby wydobywalne.

Introduction

Resources estimation is one of the most fundamental tasks of the hydrocarbon reservoir management process. This applies to all types of the reservoirs. However, it is particularly important for unconventional reservoirs due to their more difficult characterization and mechanisms of hydrocarbon recovery. This conclusion applies to both deterministic and stochastic techniques of resources estimation. The complexity of the problem of resources estimation depends also upon the type of resources to be determined. It is more straightforward for the case of static quantities such as GOIP and much more complicated for recoverable resources as a dynamic quantity.

Among various standard methods used for the purpose of the resource estimation the most reliable, yet also most time-consuming, is the reservoir modelling and simulations. On the other hand, other popular methods, such as production decline curve analysis and material balance analysis are less stringent but also faster and quite effective. Unfortunately, the material balance approach as a method based on the semi-steady state approximation cannot be applied to unconventional reservoirs (shale gas, tight gas, etc.), that typically produce under the transient conditions for all its production life-time. Therefore, the only applicable option is the production decline analysis.

The paper concentrates on the application of this analysis to gas shale formations discovered recently in Poland. It includes the comparative analysis of various types of decline curve models and their results as methods of resource estimation for typical shale gas formations in Poland. The investigation was performed as a part of research project "Blue Gas" sponsored by National Center of Research and Development. The results presented in the paper are obtained by in house programing tools and Eclipse reservoir simulator [3].

Production decline curve models

Decline curve models belong to the data modelling methods that, in general, solve the following problem: given the set of observation data (here, production rates or totals) reported for varying independent variables (here time of observation) and a parametric model describing the production processes find the set of parameter values that best describe the observation results.

Upon solving the above problem the resulting model can be used to find various characteristics of the process including recoverable resources according to their particular definition. The methods of production decline curves [1] have been commonly used in the area of petroleum management for decades. They are based on some heuristic laws describing the dependence of production rates (q) or totals (G_p) upon the time (t).

For conventional hydrocarbon reservoirs the classical models by Arps are used of the following general formula:

$$\frac{1}{q}\frac{dq}{dt} = -Kq^n$$

where: K and n are curve parameters that describe the types of models (exponential: $n = 0$, hyperbolic: $0 < n < 1$, harmonic: $n = 1$).

These models (or their combination) are also used to analyse production from unconventional reservoirs. However, several new models were also proposed for these new objects. They include:

- Stretched Exponential [7]: $q = q_i \exp\left\{-\left(\frac{t}{\tau}\right)^n\right\}$, three parameter model: q_i, n, τ,
- Power-Low Exponential [5]: $q = q_1 \exp\{-D_i t^n - D_\infty t\}$, four parameter model: q_i, n, D_i, D_∞,
- Duong's curve [2]: $q = q_i t^{-m} \exp\{b(t^{1-m} - 1)\}$, three parameter model: q_i, m, b,
- Logistic Growth Model [8]: $q = \frac{dG_p}{dt}$, $G_p = \frac{Kt^n}{a + t^n}$, three parameter model: K, n, a.

Determination of the model parameters by the production history math process results in the estimating of the dynamic (recoverable) resources found for individual wells and their groups when the production process description is completed with the termination conditions. The full regression analysis or another applicable technique of the matching phase results also in uncertainty analysis of the results obtained.

Comparable analysis of decline curve models

The procedure used to analyse various production decline curve models and their effectiveness to assess the recoverable resources included the following stages:

1) the construction and dynamic calibration (where applicable) of reservoir simulation models [6] of shale formations characterized by parameters typical for the objects discovered recently in Poland with respect to both geological parameters and well zone stimulation parameters. The use of reservoir simulation results instead of the directly measured production data were caused by very limited observation sets,
2) the matching process of several selected decline curve models to multiple simulation results treated as observation data,
3) determination of the recoverable resources by the decline curve models and their comparison with the reservoir simulation results for these resources.

Single-phase models

At the initial stage of investigation when very limited calibration data were available, a single-phase one-well models of shale formations characterized by typical parameters were constructed. A general scheme of these 3-D models is shown in Fig. 1 where a horizontal well with a variable number of fracture stimulation stages completes the drainage area of a shale formation. Each stimulated area (SRV) consists of a discrete hydraulic fracture and a continuous volume of secondary fractures modelled as a double porosity – single permeability flow system. The reservoir part outside the SRV, called the extended reservoir volume (XRV), is modelled as a single porosity – single permeability flow system.

Introductory simulation analysis showed the sensitivity of the gas production curve to various geological and

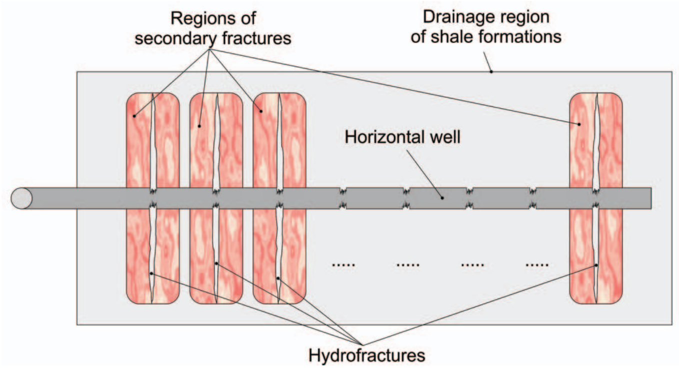

Fig. 1. Schematic of shale formation simulation model

Table 1. Errors of recoverable resource estimates, G_p, averaged over 44 different well stimulation parameters by the application of various decline curves. Models with matrix permeability, k_m = 100 nD and no adsorbed gas

Production time / matching time [years]	Decline Curve			
	Hyperbolic	Stretched exponential	Duong's	Logistic
1/½	26%	27%	24%	23%
2/½	17%	18%	18%	15%
5/1	8%	4%	8%	4%

well-stimulation parameters is quite different. This was the reason to distinguish between two sets of these parameters: the parameters from the first set were defined constant and did not very among the investigated models. These are: gas contents (100% methane), reservoir temperature (T_{res} = 100°C), initial reservoir pressure (P_i = 310 b), the model sizes ($L \times W \times H = 976 \times 500 \times 11$ m), matrix porosity (ϕ_m = 5%), secondary fracture porosity (ϕ_f = 3%), secondary fracture permeability (k_f = 0.1 mD), matrix-fracture coupling (σ = 0.05 m^{-2}), well horizontal section length (L_h = 776 m), hydro-fracture transmissibility (T_{fh} = 200 mD × m). The reservoir and well stimulation parameters from the second set varied in different models. These are: matrix permeability: (k_m = 10÷1000 nD), adsorbed gas (0% and 50% of total OGIP), gas diffusion constant (D = 0÷0.006 m^2/d), number of stimulation sections (n_f = 4, 8, 16), hydrofracture length (l_f = 250÷550 m), single stimulation area width (d_f = 11÷120 m).

The simulation models were run under the controlling conditions of constant bottom hole pressure (P_{BHP} = 35 b) till one of two final conditions were met (either t_{max} = 30 year, or q_{min} = 1 Nm^3/min). The results of gas production rate vs time were then used to match selected decline curves and determine their parameters. Four curves of most distinctive results were selected for detailed analysis: Hyperbolic, Stretched Exponential, Duong's and Logistic Growth. Three periods of production data used in the matching process were: (a) 1-year of production with the last half-year data for matching, (b) 2-years of production with last half-year data for matching, (c) 5-years of production with the last year data for matching.

Quantitative criterion of the curve model effectiveness was the relative error of recoverable resources (defined by final total production under given termination conditions) as compared to the corresponding simulation results. The errors were averaged for each curve over all of the (44) different models w/r to varying well-stimulation parameters presented above (n_f, l_f, d_f).

Table 1 presents these averaged errors for the case of fixed matrix permeability, k_m = 100 nD without adsorbed gas. The errors for various curves are quite close to one another and they reduce for longer periods of the matching process. It is worth noting that the quality of the match is high for all the three periods (Fig. 2, 3). Yet the extrapolation of these curves that is responsible for the resource estimation shows much larger discrepancy for one year's data match (Fig. 4) than for five-years' data match (Fig. 5).

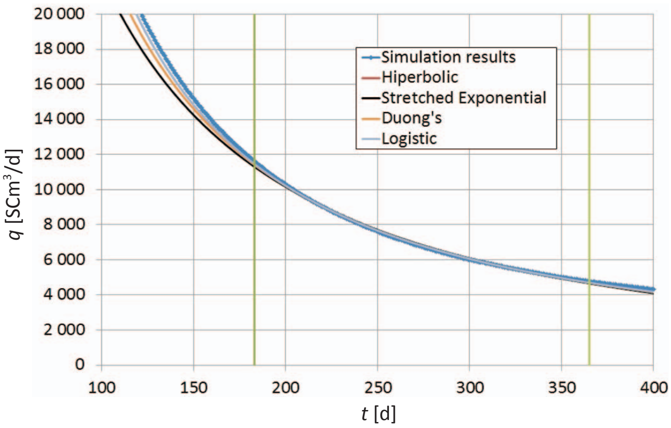

Fig. 2. Matching of production decline curves to the simulation results. Models with k_m = 100 nD, and no adsorbed gas. Production time: 1 year, matching time: ½ year

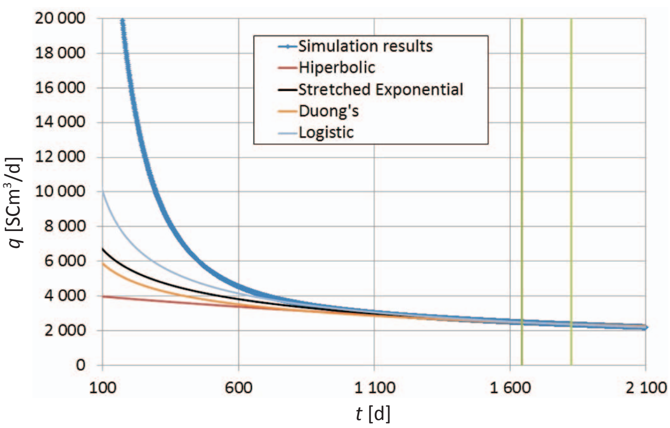

Fig. 3. Matching of production decline curves to the simulation results. Models with k_m = 100 nD and no adsorbed gas. Production time: 5 years, matching time: 1 year

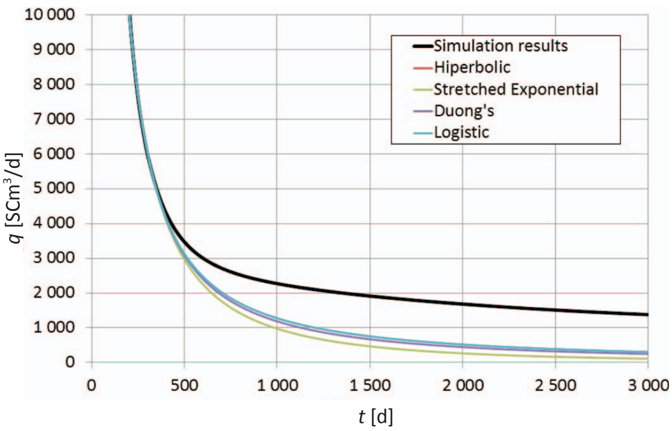

Fig. 4. Extrapolation of production profile for curves matched during last ½ year of 1 year's production period. Comparison with simulation results. Models with k_m = 100 nD and no desorbed gas

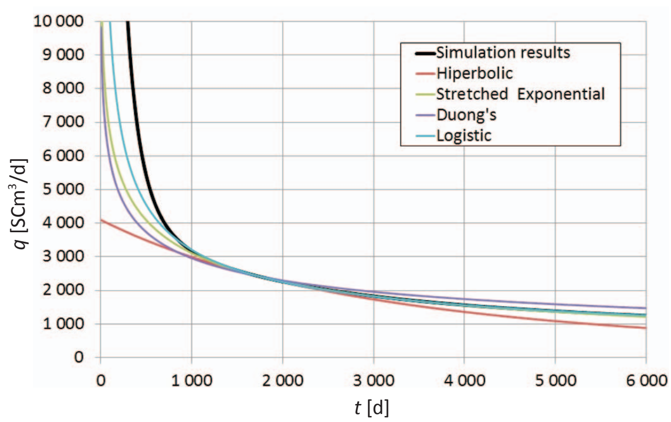

Fig. 5. Extrapolation of production profile for curves matched during last year of 5 year's production period. Comparison with simulation results. Models with k_m = 100 nD and no adsorbed gas

Analogous results are obtained for other cases. Table 2 shows results for the case with adsorbed gas. Although comparable, the results become distinctively better matched for Stretched Exponential and Logistic Growth Curves of the longest match period of 5 year. Table 3 and 4 presents results for the cases of different matrix permeability (10 nD and 1000 nD, resp.) For both cases and 5 years' match period the best results (the smallest error) is produced by the Stretched Exponential Curve while the Logistic Growth Curve is the best for the 1 year's match period.

Table 3. Errors of recoverable resource estimates G_p averaged over 44 different well stimulation parameters by the application of various decline curves. Models with matrix permeability k_m = 10 nD and adsorbed gas

Production time / matching time [years]	Decline Curve			
	Hyperbolic	Stretched exponential	Duong's	Logistic
1/½	40%	42%	39%	26%
2/½	22%	17%	14%	12%
5/1	7%	3%	25%	12%

Table 2. Errors of recoverable resource estimates G_p averaged over 44 different well stimulation parameters by the application of various decline curves. Models with matrix permeability k_m = 100 nD and adsorbed gas

Production time / matching time [years]	Decline Curve			
	Hyperbolic	Stretched exponential	Duong's	Logistic
1/½	32%	39%	35%	30%
2/½	25%	24%	21%	20%
5/1	16%	8%	25%	10%

Table 4. Errors of recoverable resource estimates G_p averaged over 44 different well stimulation parameters by the application of various decline curves. Models with matrix permeability k_m = 1000 nD and adsorbed gas

Production time / matching time [years]	Decline Curve			
	Hyperbolic	Stretched exponential	Duong's	Logistic
1/½	28%	33%	26%	25%
2/½	35%	21%	14%	22%
5/1	20%	10%	36%	15%

Double-phase models

After the analysis had been made, new date were available from the shale formations in Poland that consisted of a standard set of reservoir and well stimulation data supplemented with very limited production data (well production test after fracturing stimulation). These data were limited to the final water flowback and maximum gas production rate [4]. Based on the above information double-phase reservoir simulation model was constructed characterized by the following parameters: reservoir depth, D = 3300 m – 3600 m b.s.l. effective thickness, h = 100 m, initial reservoir pressure, P_{ini} = 360 bar, reservoir temperature, T_r = 90°C, matrix porosity, ϕ_n = 3%, matrix permeability, k_m = 150 nD, fracture density, n_f = 1 m^{-1}, effective porosity of induced fractures, ϕ_f = 0.2%, effective permeability of induced fractures, k_f = 0.1 mD, well horizontal section length, L_f = 1000 m, well radius 5 ½", hydraulic fracture width, w_f = 5 mm, hydraulic fracture half-length, l_f = 150 m, hydraulic fracture height, h_f = 100 m, total water injected per

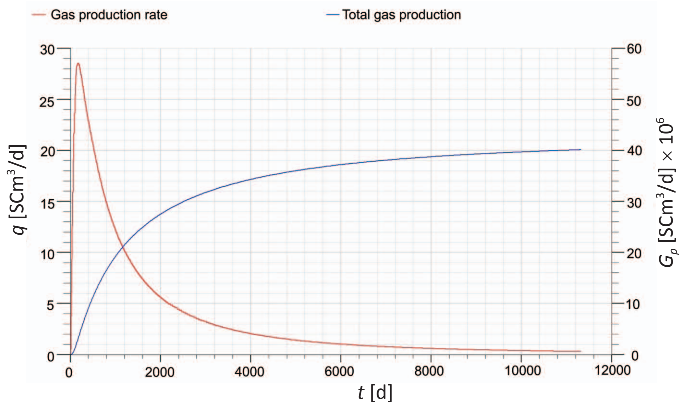

Fig. 6. Durable-phase model. Gas production rate and total

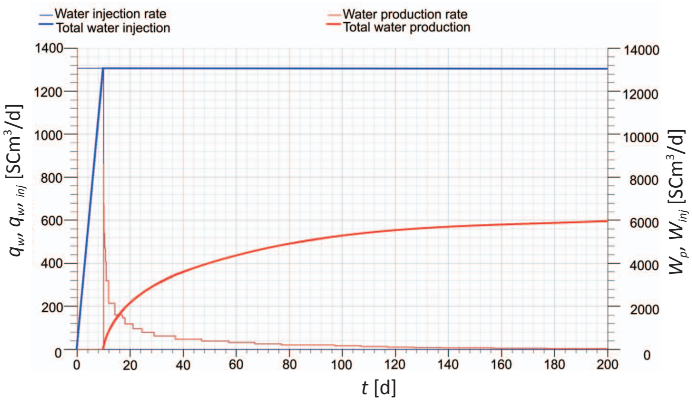

Fig. 7. Double-phase model. Water injection rate and total. Water production rate and total

fracture section W_{inj} = 1310 Nm³, no. of fracture sections, n_f = 10, water flowback ≈ 45%, maximum gas production rate, $q_{g,max}$ ≈ 30 000 Nm³/d. The results of the model calibration are shown in Fig. 6 and 7. The calibration process allowed to determine the lacking parameters of the model, such as SRV volume, matrix-fracture coupling, water and gas saturations, relative permeabilities. The observed water flowback and gas rate also required using 3-porosity, 2-permeability flow system in the SRV region and 2-porosity, 1-permeability flow system in the XRV region.

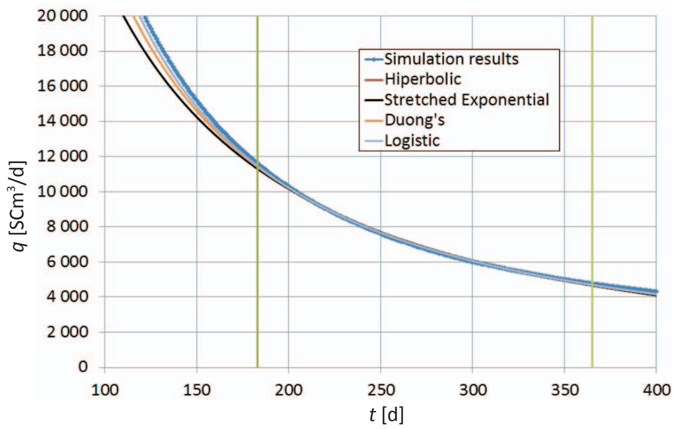

Fig. 8. Matching of production decline curves to the simulation results. Double-phase model with no adsorbed gas. Production time: 1 year, matching time: ½ year

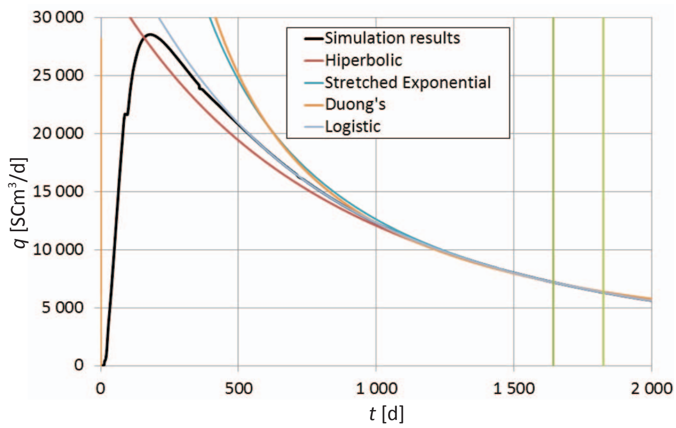

Fig. 9. Matching of production decline curves to the simulation results. Double-phase model with no adsorbed gas. Production time: 5 years, matching time: 1 year

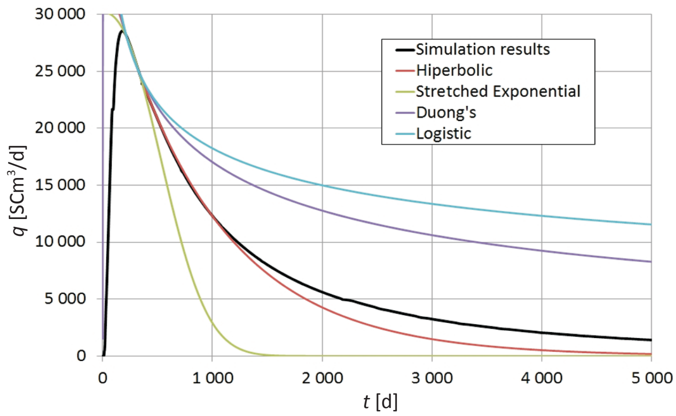

Fig. 10. Extrapolation of production profile for curves matched during last ½ year of 1 year's production period. Comparison with simulation results. Double-phase model with no adsorbed gas

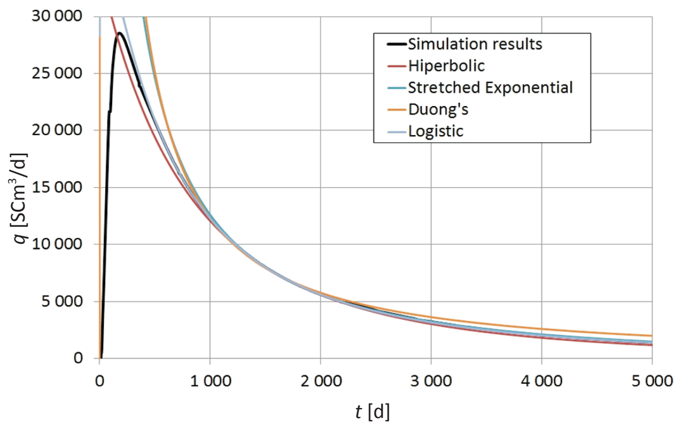

Fig. 11. Extrapolation of production profile for curves matched during last year of 5 years' production period. Comparison with simulation results. Double-phase model with no adsorbed gas

The calibrated simulation model was then run by analogy with the previous models under constant bottom hole pressure condition until the minimum rate or maximum simulation time were reached. Four previously selected decline curves were matched to the obtained simulation results of q vs t for the three different production and matching periods as before (Fig. 8 and 9). One year's matching procedure produced very inaccurate results for recoverable resources (Fig. 10 and Table 5). Two and five years' matching procedure resulted in much better accuracy of resource estimates especially those obtained by the Logistic Growth Curve (Table 5 and Fig. 11).

Table 5. Errors of recoverable resource estimates, G_p, averaged over 44 different well stimulation parameters by the application of various decline curves. Double-phase model of the calibrated shale formation discovered and tested in Poland

Production time / matching time [years]	Decline Curve			
	Hyperbolic	Stretched exponential	Duong's	Logistic
1/½	18%	55%	454%	89%
2/½	20%	25%	124%	11%
5/1	6%	1%	12%	0.34%

Conclusions

Investigations of production decline analysis by methods of various decline curve models in order to obtain a reliable estimation of recoverable resources from the shale formations discovered in Poland shows insufficient accuracy of the method if based on a short time (one year) production data. At least two-years' production data should be used for the method to provide the reliable resource estimations. Production data from the five year's period analysed with the proper decline curve model most likely result in the resource estimation error below 10%. Statistical analysis of the resource estimation results points to the Stretched Exponential and Logistic Growth Curve as the most accurate methods of production forecast for shale formations in Poland. The presence of adsorbed gas in significant quantities relative to the total OGIP reduces the accuracy of the resource estimates by the decline curve analysis.

It should be noted that the above conclusions, although based on real reservoirs and well-completion parameters of shale formations discovered in Poland, refer to rather limited number of cases available at the time of this investigation.

The investigation will be continued when the new data are available.

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