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TECHNICAL SCIENCES

Gasohydrodynamic Testing of Gas and Gas-Condensate Reservoirs and Wells

Gulbahar Mammadova[1], Shafag Habibullayeva[2], Aytan Omarova[3], and Aygun Bayramova[4*]

Abstract. *The article outlines the steady-state gasohydrodynamic methods used for testing gas and gas-condensate reservoirs and wells. To select downhole equipment for wells characterized by abnormally high reservoir pressure, indicator diagrams were constructed in the form of curved lines. As a result of these studies, all reservoir and well parameters, including optimal flow rates, drawdowns, allowable dynamic bottomhole pressures, the amount of mechanical impurities, reservoir pressure and temperature, were determined. A two-term inflow equation was used, and the coefficients a and b were determined graphically. In addition, formulas for calculating these coefficients for hydrodynamically complete (perfect) wells are provided. For hydrodynamically incomplete (imperfect) wells, formulas for the incompleteness coefficients* C_1*,* C_2*,* C_3*, and* C_n*, as well as for the inflow equation parameters a and b, are presented. The values of these coefficients and parameters were also determined using numerical methods, and the corresponding formulas are provided. The indicator diagrams, i.e., the curves showing the dependence of gas flow rates on dynamic bottomhole pressures, were linearized, and the parameters a and b of the inflow equation were determined graphically. The indicator curves pass through the origin, are concave with respect to the flow-rate (abscissa) axis, and represent monotonically increasing functional relationships.*

Keywords: *gas reservoirs, gas-condensate reservoirs, gas wells, gas-condensate wells, two-term inflow equation, equation parameters, imperfection coefficients, degree of reservoir penetration, nature of reservoir penetration*

[1]Azerbaijan State Oil and Industry University, PhD in Technical Sciences, Baku, Azerbaijan
[2]Azerbaijan State Oil and Industry University, Baku, Azerbaijan
[3]Azerbaijan State Oil and Industry University, PhD student, Baku, Azerbaijan
[4]Western Caspian University, PhD in Technical Sciences, Baku, Azerbaijan
[*]Corresponding author. E-mail: aygun.b2274@gmail.com
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Qaz və qaz-kondensat laylarının və quyularının qazohidrodinamik tədqiqatları

Gülbahar Məmmədova[1], Şəfəq Həbibullayeva[2], Aytən Ömərova[3], Aygün Bayramova[4*]

Xülasə. *Məqalədə qaz və qaz-kondensat laylarının və quyularının qazohidrodinamik tədqiqatının stasionar üsulları şərh edilmişdir. Anomal yüksək lay təzyiqinə malik bu quyular üçün quyudaxili avadanlığın seçilməsi məqsədilə indikator diaqramları əyrilər şəklində qurulmuşdur. Bu tədqiqatlar nəticəsində layın və quyunun bütün parametrləri (optimal debitlər, depressiyalar, buraxıla bilən dinamik dib təzyiqləri, mexaniki qarışıqların miqdarı, lay təzyiqi, lay temperaturu və s.) müəyyən edilmişdir. İkihədli axın tənliyindən istifadə edilmiş, tənliyin a və b əmsallarının qiymətləri qrafiki yolla təyin edilmişdir; bu əmsalların hesablanması üçün hidrodinamik tamamlanmış quyulara aid düsturlar da verilmişdir. Hidrodinamik tamamlanmamış quyular üçün C_1, C_2, C_3 və C_n natamamlıq əmsallarının, həmçinin a və b əmsallarının hesablanması üçün lazım olan düsturlar təqdim edilmişdir. Bu əmsalların qiymətləri ədədi üsullarla da təyin edilmişdir (müvafiq düsturlar verilmişdir). İndikator əyriləri, yəni qaz debitlərinin quyudibi dinamik təzyiqlərdən asılılığını göstərən əyrilər qurulmuş, axın tənliyinin a və b əmsalları qrafiki yolla təyin edilmişdir. İndikator əyriləri koordinat başlanğıcından keçir, debitlər (absis) oxuna nisbətən çökəkdir və artan monoton funksional asılılıqları ifadə edir.*

Açar sözlər: *qaz layları, qaz-kondensat layları, qaz quyuları, qaz-kondensat quyuları, ikihədli axın tənliyi, tənliyin parametrləri, natamamlıq əmsalları, layın açılma dərəcəsi, layın açılma xarakteri*

[1]Azərbaycan Dövlət Neft və Sənaye Universiteti, texnika elmləri üzrə fəlsəfə doktoru, Bakı, Azərbaycan
[2]Azərbaycan Dövlət Neft və Sənaye Universiteti, Bakı, Azərbaycan
[3]Azərbaycan Dövlət Neft və Sənaye Universiteti, doktorant, Bakı, Azərbaycan
[4]Qərbi Kaspi Universiteti, texnika elmləri üzrə fəlsəfə doktoru, Bakı, Azərbaycan
[*]Məsul müəllif. E-poçt: aygun.b2274@gmail.com
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Introduction

To select modern downhole equipment for gas and gas-condensate wells with abnormally high reservoir pressure, it is necessary to test the wells using gasohydrodynamic methods under steady-state filtration regimes. These methods are based on determining the relationships between the flow rates and dynamic bottomhole pressures of various wells. As a result of these studies, the following are determined: the dependence of the gas flow rate on the drawdown applied to the reservoir, and the changes in wellhead pressure, bottomhole pressure, annulus pressure, and temperature as a function of the well flow rate; the amount of liquid and solid impurities produced during various operating regimes of the well; deformations and failures of the bottomhole zone of the reservoir; the accumulation and removal of failure products, and filtration resistance; the technological regime of well operation, taking various factors into account; the hydraulic resistance coefficient; and the effectiveness of remedial and preventive maintenance during additional perforations in the well, bottomhole consolidation, bridge setting, etc (Ahmed, 2006; Ahmed, 2019; Briksman et al., 1996). Testing under steady-state regimes is conducted starting from lower flow rates and moving toward higher flow rates (forward course). In each regime, complete stability of pressure and flow rate must be achieved. The acquired data are used to construct indicator diagrams. The first point is selected where the pressure and flow rate remain unchanged. After measuring the stabilized pressure, flow rate, and temperature at the bottomhole, wellhead, and annulus, and determining the amount of liquid and solid impurities in the given regime, the well is shut in until P_{res} (reservoir pressure) is reached. The pressure buildup process is also continuously recorded. After processing (interpreting) the obtained pressure buildup curve, the reservoir parameters are determined. Here, it is also established whether there is a reservoir pressure anomaly; by comparing it with the normal reservoir pressure, it is determined whether it is greater or smaller (Craft & Hawkins, 1959).

Materials and Methods

This method is conducted with no fewer than 4–5 forward regimes and 2–3 reverse regimes.Under steady-state filtration regimes, the two-term formula for processing test results has the following form:

$$P_{res}^2 - P_{wf}^2 = aQ + bQ^2 \qquad (1)$$

Where *a* and *b* are the filtration resistance coefficients, respectively, which depend on the design parameters of the bottomhole zone of the reservoir; *Q* is the well flow rate; P_{res} and P_{wf} are the reservoir and dynamic bottomhole pressures, respectively (Gimatudinov, 1978; Katz et al., 1959; Lee, 2003). For hydrodynamically complete wells under radial filtration, coefficients *a* and *b* are expressed by the following formulas:

$$a = \frac{\mu z P_{at} T_{res}}{\pi k h T_{st}} ln \frac{R_c}{r_w} \qquad (2)$$

$$b = \frac{P_{at}^2 P_{at} T_{res}}{2\pi^2 l h^2 T_{st} r_w} (1 - \frac{r_w}{R_c}) \qquad (3)$$

For an incomplete well, based on the degree and nature of reservoir penetration, these coefficients are expressed as follows:

$$a = a^*(ln \frac{r_w}{R_c} + C_1 + C_2), a^* = \frac{\mu z P_{at} T_{res}}{2\pi^2 \, ln \, T_{st}} \qquad (4)$$

$$b = b^*(\frac{1}{r_w} - \frac{1}{R_c} + C_3 + C_4), b^* = \frac{P_{at} z P_{at} T_{res}}{2\pi^2 \, ln \, T_{st}} \qquad (5)$$

Where C_1 , C_2 and C_3 , C_4 are the incompleteness coefficients determined according to the degree and characteristics of reservoir penetration, respectively:

$$C_1 = \frac{1}{h} ln \, \overline{h} + \frac{1-\overline{h}}{\overline{h}} ln \frac{b}{R_s} \qquad (6)$$

$$C_2 = 1/\overline{h} \qquad (7)$$

Where $\overline{h} = h_{penet}/h$ is the relative penetration thickness of the reservoir;

$R_s = r_w/h$ is the relative radius of the well, and $\delta = 1,6(1 - \overline{h}^2)$.

The values of coefficients C_1 , C_2 depend significantly on the non-uniformity of the porous medium's permeability. For uniform anisotropic reservoirs:

$$C_1 = \frac{1}{v} ln \frac{\overline{R}^v - x}{\overline{h}} - ln \, \overline{R} \qquad (8)$$

$$C_2 = (C_1 + ln \, \overline{R})/\overline{h} \, ln \, \overline{R} \qquad (9)$$

Where $v = \sqrt{\frac{k_v}{k_h}}$- is the anisotropy parameter; k_v and k_h are the vertical and horizontal permeabilities of the reservoir, respectively; $\overline{R} = R_c/r_w$ is the dimensionless radius, and $x = 1 - \overline{h}$.

Taking into account the filtration resistance coefficients from (8) and (9), incomplete wells penetrating anisotropic reservoirs based on the degree of reservoir penetration are determined by the following formula (Dake, 1978):

$$a = \frac{a^*}{v} ln \frac{R^v - x}{\overline{h}} \quad (10)$$

$$b = b^* \frac{ln(R/v - x)/\overline{h}}{\overline{h} v \, ln \, \overline{R}} \quad (11)$$

Determining coefficients C_3 and C_4 is quite complex, which is related to the shape and dimensions of the perforation holes and their changes during well operation (Guo et al., 2007; Horne, 1995; Ikoku, 1984). Studies have shown that the productivity of gas wells depends on the relative surface area of the holes *f*, meaning:

$$f = F_{st}/F \quad (12)$$

Where F_{st} is the surface area of the perforation holes;
F is the surface area of 1 meter of the wellbore.

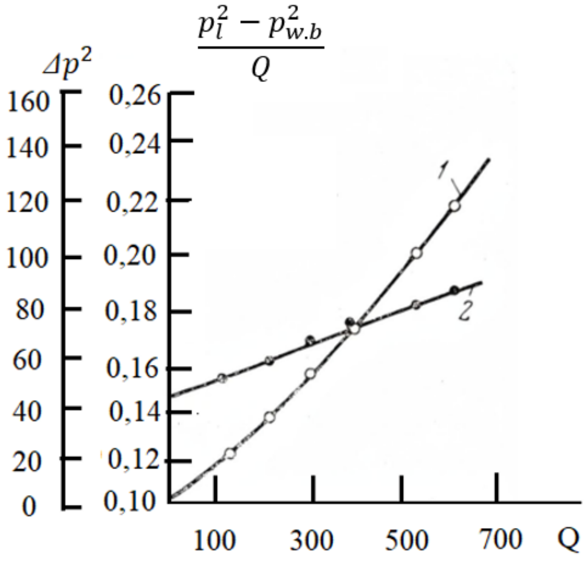

Figure 1
Indicator diagrams in coordinates:
1) $\Delta p^2 = p_l^2 - p_{w.b}^2 \rightarrow Q$;
2) $(p_l^2 - p_{w.b}^2)/Q \rightarrow Q$

The maximum increase in well productivity occurs within the interval
$\overline{f} = 0 - 0{,}150$.

$$C_3 = h/nR_0; C_4 = h^2/3n^2R_0^2 \quad (13)$$

Where h is the reservoir thickness, m; n is the number of perforation holes; R_0 is the cavity radius (Mammadova, 2014; Matthews & Russell, 1967).

In Figure 1, the indicator diagrams are given in the coordinates

$$1)\Delta p^2 = p_l^2 - p_{w.b}^2 \rightarrow Q; \quad 2)(p_l^2 - p_{w.b}^2)/Q \rightarrow Q$$

The well test results under steady-state filtration regimes are interpreted according to formula (1); coefficients a and b are determined analytically or graphically (Iskandarov et al., 2025; Ismayilov et al., 2025).

When determining graphically, coefficient a is found as the intercept cut by the straight line 2 on the ordinate axis, and coefficient b is found as the tangent of the slope angle of this straight line to the abscissa axis (Mustafayev, & Mikailova, 2017).

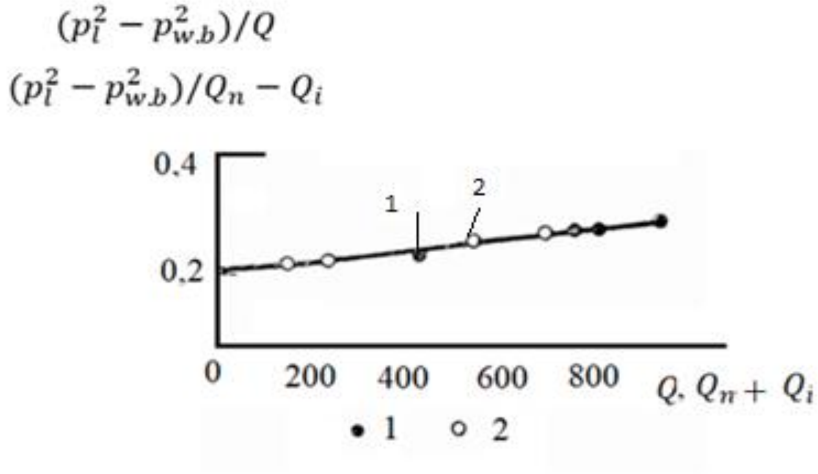

Figure 2

Dependencies at unknown reservoir pressure:

$$1)\ \frac{p_l^2 - p_{w.b}^2}{Q} \text{ from } Q; \qquad 2)\ \frac{p_l^2 - p_{w.b}^2}{Q_n - Q_i} \text{ from } Q_n + Q_i$$

The values of these coefficients are determined numerically using the following formulas:

$$a = \frac{\sum\frac{\Delta P^2}{Q}\sum Q^2 - \sum Q \sum \Delta P^2}{N\sum Q^2 - (\sum Q)^2} \qquad (14)$$

$$b = \frac{N\sum \Delta P^2 - \sum Q \sum\frac{\Delta P^2}{Q}}{N\sum Q^2 - (\sum Q)^2} \qquad (15)$$

Where N is the number of regimes.

$$\frac{\sum\frac{P_{w.b.i}^2 - P_{w.b.n}^2}{Q_n - Q_i}\sum(Q_n - Q_i)^2 - \sum(Q_n - Q_i)\sum\frac{(P_{w.b.i}^2 - P_{w.b.n}^2)(Q_n + Q_i)}{Q_n - Q_i}}{N_1\sum(Q_n - Q_i)^2 - \left[\sum(Q_n - Q_i)\right]^2} \qquad (16)$$

$$b = \frac{N_1\sum\frac{(P_{w.b.i}^2 - P_{w.b.n}^2)(Q + Q_i)}{Q_n - Q_i} - \sum(Q_n + Q_i)\sum\frac{P_{w.b.i}^2 - P_{w.b.n}^2}{Q_n - Q_i}}{N\sum Q^2 - (\sum Q)^2},$$

$$N_1 \sum(Q_n + Q_i - [\sum(Q_n + Q_i)]^2 \quad (17)$$

Where N_1 is the number of combinations and determined by this formula:

$$N_1 = \sum(m-1)$$

Figure 3 shows the dependence of $P_{res}^2 - P_{w.b}^2$ on Q.

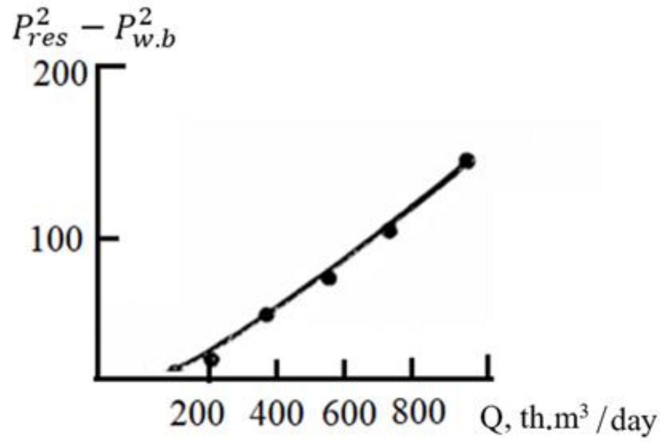

Figure 3
Dependence of $P_{res}^2 - P_{w.b}^2$ on Q

Various factors influence the shape of the indicator diagrams: inaccuracies in reservoir (especially abnormal) and bottomhole pressures, the presence of liquid in the wellbore, errors in determining the hydraulic resistance coefficient, etc. In such cases, approximate methods for processing test results are utilized (Mirzajanzade, Kovalev, et al., 1962).

1. Reservoir pressure is not fully restored

Assume that the actual reservoir pressure differs from the true one by a value δ_1. Then:

$$P_{res} = P'_{res} - \delta_1 \quad (18)$$

Where P'_{res} is the measured (actual) reservoir pressure.

$$P_{res}^2 - P_{w.b}^2 = aQ + bQ^2 - \Delta P_{res} \quad (19)$$

Where,

$$\Delta P_{res} = P'_{res}\delta_1 + \delta_1^2 \quad (20)$$

In this case, the indicator curve should be processed in coordinates

$(P_{res}^2 - P_{w.b}^2)Q$ and Q coordinates.

Then the true reservoir pressure is found as follows:

$$P_{res} = \sqrt{{P'_{res}}^2 + \Delta P_{res}} \quad (21)$$

2. Bottomhole dynamic pressure is not restored. Assume that the bottomhole pressure has not stabilized by δ_2 , meaning:

$$P_{w.b} = P'_{w.b} - \delta_2 \quad (22)$$

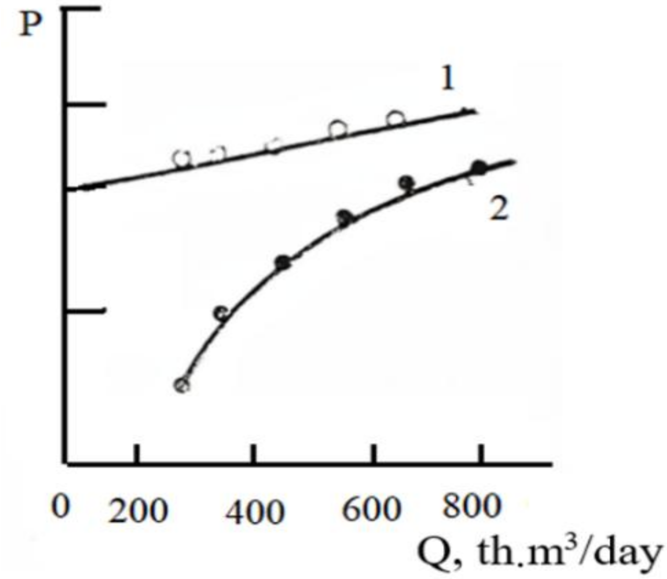

Figure 4

Indicator curves in coordinates

$$1)\, \frac{P_{res}^2 - P_{w.b}^2 + \Delta P_{res}}{Q};\, Q; \quad 2)({P'_{res}}^2 - P_{w.b}^2)/Qw$$

Figure 4 shows the indicator curves as a function of Q in coordinates 1) $(P_{res}^2 - P_{w.b}^2 + \Delta P_{res})Q$; 2)$(P_{res}^2 - P_{w.b}^2)Q$, or graphically. Here, *i* =1,2,3..., *m* is the number of regimes, and *n* is the serial number of the regimes.

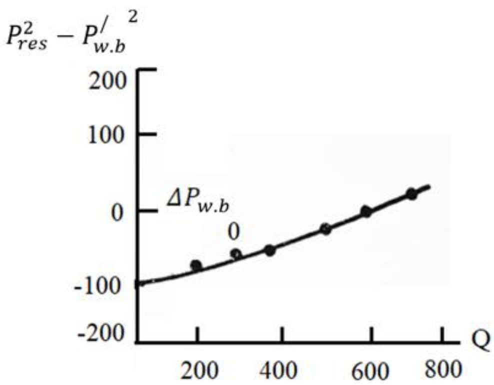

Figure 5

Indicator curve in coordinates $P_{res}^2 - {P'_{w.b}}^2$

In Figure 5, the indicator curves are selected in Q coordinates $P_{res}^2 = {P'_{w.b}}^2$.

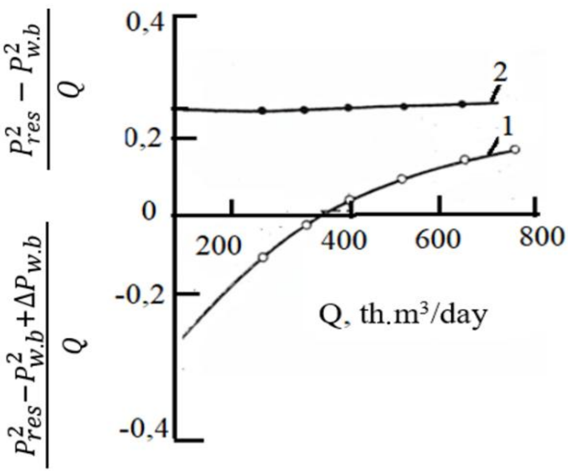

Figure 6
Dependency graphs

$$1)\ (P_{res}^2 - P'^{\,2}_{w.b})/Q;\ Q;\quad 2)\ \frac{(P_{res}^2 - P'^{\,2}_{w.b} - P_{w.b})}{Q};\ Q$$

In Figure 6, the dependencies 1) $(P_{res}^2 - P'^{\,2}_{w.b})Q$ and Q; 2) $\frac{(P_{res}^2 - P'^{\,2}_{w.b} - P_{w.b})}{Q}$ vs Q are given. Then, by analogy with the previous case, it is determined:

$$P_{res}^2 - P'^{\,2}_{w.b} = aQ + bQ^2 - \Delta P_{res} \quad (23)$$

Where,

$$\Delta P_{w.b} = 2P'_{w.b}\delta_2 - \delta_2^2 \quad (24)$$

In this case, the curve of the dependence of $P_{res}^2 - P'^{\,2}_{w.b}$ on Q will look like the form shown in Fig. 5. As can be seen, a segment equal to $\Delta P_{w.b}$ is intercepted on the ordinate axis (when Q = 0).

$$\Delta P_{w.b0} = 2P_{res}\delta_2 + \delta_2^2 \quad (25)$$

As a result of processing indicator curve 2 (Fig. 6), coefficients *a* and *b* are determined, and the $\Delta P_{w.b}$ value can be found for each regime according to the known δ_2.

3. The hydraulic resistance coefficient is known.

In this case:

$$P_{res}^2 - P_{w.b}^2 e^{2s} = aQ + (b + \theta)Q^2 \quad (26)$$

Where,

$$s = 0{,}03415 \frac{\overline{\rho} h}{z_{av} T_{av}} \quad (27)$$

$$\theta = 0{,}0133\lambda \frac{z_{av}^2 T_{av}^2}{D^5}(e^{2s} - 1) \quad (28)$$

Figure 7 presents indicator diagrams based on the test results in the following coordin0ates:

$$1),3)\ (P_{res}^2 - P_{w.b}^{\,2});\ (P_{res}^2 - P_{w.b}^2)/Q;\ Q;$$

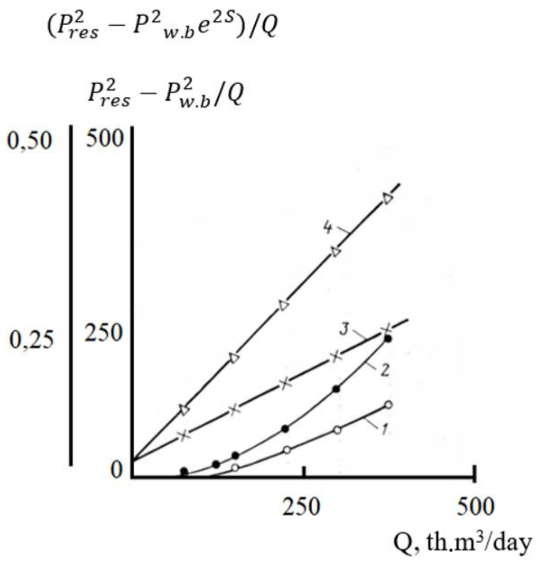

Figure 7
Indicator diagrams of survey results with coordinates

$$1)\ (P_{res}^2 - P_{w.b}{}^2); \qquad 3)\ (P_{res}^2 - P_{w.b}^2)/Q; Q$$

$$2)\ (P_{res}^2 - P_{w.b}^2 e^{2s}); \qquad 4)\ (P_{res}^2 - P_{w.b}^2 e^{2s})/Q; Q$$

Based on the test results, the indicator diagram of the dependence of

2) $(P_{res}^2 - P_{w.b}^2 e^{2s})$; 4) $(P_{res}^2 - P_{w.b}^2 e^{2s})/Q\ on\ Q$ is constructed.

The straight line obtained intercepts a segment on the ordinate axis corresponding to a, and the tangent of the slope of this straight line is equal to $b + \theta$.

As Figure 7 presents, coefficient a is identical for both processing methods, while the tangent of the slope angle of straight line 4, determined according to formula (26), is larger by θ compared to the tangent of the slope angle of line 3 (Mustafayev et al., 2017; Rasulov, 2008; Society of Petroleum Engineers, n.d.; Zotov & Tverkovsky, 1970).

Conclusion and Discussion

The article outlines the gasohydrodynamic testing methods used for gas and gas-condensate reservoirs and wells.

1. To select downhole equipment for wells characterized by abnormally high reservoir pressure, gasohydrodynamic testing is conducted under steady-state filtration regimes, and indicator diagrams are constructed.
2. As a result of these studies, all reservoir and well parameters, including optimal flow rates, drawdowns, allowable dynamic bottomhole pressures, the amount of mechanical impurities, and other relevant characteristics, are determined, and the optimal operating regime for the well is established.
3. A two-term inflow equation is used, and the coefficients a and b are determined graphically. Formulas for calculating these coefficients for hydrodynamically complete wells are also provided.
4. For hydrodynamically incomplete wells, the necessary formulas for the incompleteness coefficients C_1, C_2, C_3, and C_n, as well as for the coefficients a and b, are presented. The values

of these coefficients are also determined numerically, and the corresponding formulas are provided. The indicator curves, i.e., the curves showing the dependence of gas flow rates on dynamic bottomhole pressures, are linearized, and the coefficients a and b of the inflow equation are determined graphically.

5. The indicator curves pass through the origin, are concave with respect to the flow-rate (abscissa) axis, and represent monotonically increasing functional relationships.

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