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DETERMINATION OF THE PRESSURE GRADIENT ALONG THE WELLBORE IN GAS–LIQUID WELLS

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Abstract. Accurate determination of bottomhole pressure is a critical task in the analysis and optimization of gas and gas-condensate well performance. In wells operating under liquid loading conditions, conventional methods based on wellhead or annular pressure often fail to provide sufficient accuracy due to the complex nature of multiphase flow and the impact of liquid accumulation in the wellbore. This leads to distortions in well testing interpretation and reduces the efficiency of engineering decisions. This study proposes a statistical approach to estimating bottomhole pressure in gas–liquid wells using multiple linear regression analysis. The model is developed based on field data obtained from gas hydrodynamic well testing, including downhole pressure measurements acquired with electronic gauges. Key operational and physical parameters were considered, such as gas flow rate, condensate-to-gas ratio, water-to-gas ratio, fluid density, tubing length and geometry, as well as temperature conditions. As a result, a regression equation was derived that allows accurate prediction of bottomhole pressure. Comparison with conventional methods showed that the average error is reduced by more than two times. The high coefficient of determination ($R^2 = 0.96$) confirms the adequacy and statistical significance of the model. It is demonstrated that liquid accumulation and operating conditions significantly affect the pressure gradient distribution along the wellbore. The proposed approach can be effectively applied in reservoir engineering practice and integrated into digital field development management systems.

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Keywords: bottomhole pressure, gas–liquid well, pressure gradient, liquid loading, multiple linear regression, gas-condensate wells, well testing, multiphase flow, tubing, reservoir engineering.

Annotatsiya. Quduq tubidagi bosimni aniq aniqlash gaz va gaz-kondensat quduqlari ish faoliyatini tahlil qilish va optimallashtirishda muhim vazifadir. Suyuq yuklanish sharoitida ishlaydigan quduqlarda quduq boshi yoki halqali bosimga asoslangan an'anaviy usullar ko'pincha ko'p fazali oqimning murakkab tabiati va quduq tubida suyuqlik to'planishining ta'siri tufayli etarli darajada aniqlikni ta'minlay olmaydi. Bu quduqlarni sinovdan o'tkazishni talqin qilishda buzilishlarga olib keladi va muhandislik qarorlari samaradorligini pasaytiradi. Ushbu tadqiqotda ko'p chiziqli regressiya tahlilidan foydalangan holda gaz-suyuqlik quduqlaridagi tubdagi bosimni baholash uchun statistik yondashuv taklif etiladi. Model gaz gidravlik quduqlarini sinovdan o'tkazish natijasida olingan dala ma'lumotlari, jumladan, elektron o'lchagichlar yordamida olingan quduqdagi bosim o'lchovlari asosida ishlab chiqilgan. Gaz oqimining tezligi, kondensat-gaz nisbati, suv-gaz nisbati, suyuqlik zichligi, quvur uzunligi va geometriyasi, shuningdek harorat sharoitlari kabi asosiy operatsion va fizik parametrlar ko'rib chiqildi. Natijada, quduq tubidagi bosimni aniq bashorat qilish imkonini beruvchi regressiya tenglamasi ishlab chiqildi. An'anaviy usullar bilan taqqoslash shuni ko'rsatdiki, o'rtacha xato ikki martadan ko'proq kamayadi. Aniqlanishning yuqori koeffitsienti ($R^2 = 0,96$) modelning adekvatligi va statistik ahamiyatini tasdiqlaydi. Suyuqlikning to'planishi va ish sharoitlari quduq bo'ylab bosim gradientining taqsimlanishiga sezilarli ta'sir ko'rsatishi ko'rsatilgan. Taklif etilgan yondashuvni suv omborlarini loyihalash amaliyotida samarali qo'llash va konlarni rivojlantirishni boshqarishning raqamli tizimlariga integratsiya qilish mumkin.

Kalit so'zlar: quduq tubidagi bosim, gaz-suyuqlik qudug'i, bosim gradienti, suyuqlik yuklanishi, ko'p chiziqli regressiya, gaz-kondensat quduqlari, quduqlarni sinovdan o'tkazish, ko'p fazali oqim, quvurlar, rezervuar muhandisligi.

Аннотация. Точное определение забойного давления является важнейшей задачей при анализе и оптимизации работы газовых и газоконденсатных скважин. В скважинах, работающих в условиях загрузки жидкостью, традиционные методы, основанные на измерении устьевого или кольцевого давления, часто не обеспечивают достаточной точности из-за сложной природы многофазного потока и влияния накопления жидкости в стволе скважины. Это приводит к искажениям при интерпретации результатов испытаний скважин и снижает эффективность инженерных решений. В

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данном исследовании предлагается статистический подход к оценке забойного давления в газожидкостных скважинах с использованием множественного линейного регрессионного анализа. Модель разработана на основе полевых данных, полученных в результате газогидродинамических испытаний скважин, включая измерения забойного давления, полученные с помощью электронных датчиков. Были рассмотрены ключевые эксплуатационные и физические параметры, такие как расход газа, соотношение конденсата и газа, соотношение воды и газа, плотность жидкости, длина и геометрия трубопровода, а также температурные условия. В результате было получено уравнение регрессии, позволяющее точно прогнозировать забойное давление в скважине. Сравнение с традиционными методами показало, что средняя ошибка уменьшается более чем в два раза. Высокий коэффициент детерминации (R2 = 0,96) подтверждает адекватность и статистическую значимость модели. Показано, что накопление жидкости и условия эксплуатации существенно влияют на распределение градиента давления вдоль ствола скважины. Предложенный подход может быть эффективно применен в практике разработки месторождений и интегрирован в цифровые системы управления разработкой месторождений.

Ключевые слова: забойное давление, газожидкостная скважина, градиент давления, загрузка жидкостью, множественная линейная регрессия, газоконденсатные скважины, испытания скважин, многофазный поток, насосно–компрессорные трубы, разработка месторождений.

INTRODUCTION.

Determination of bottomhole pressure is one of the key tasks in the analysis and control of gas and gas-condensate well operating conditions. In routine well operation, annular pressure is widely used to calculate bottomhole pressure. However, as demonstrated by Korotaev Yu.P. [1], when the tubing shoe is submerged in liquid, the surface annular pressure does not provide the accuracy required for determining bottomhole pressure either while the well is flowing through the production tubing or after the well has been shut in.

A number of methods are currently available for determining bottomhole pressure in wells operating with liquid entrainment, including methods based on the wellhead pressure measured in the tubing [1,2,4–6]. However, under the conditions encountered in gas–liquid wells in Uzbekistan's fields, these methods often yield substantially different results, thereby reducing the reliability of gas-well test calculations.

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Improving the accuracy of pressure determination along the wellbore is of considerable practical importance. Errors in pressure estimation distort well productivity characteristics, lead to incorrect selection of operating conditions, and reduce the efficiency of gas gathering and treatment systems [3]. Accordingly, the development of more accurate methods for calculating bottomhole pressure with due consideration of the specific features of gas–liquid flow is an important and timely task.

In recent years, methods of mathematical statistics have been increasingly applied in the oil and gas industry because they make it possible to account for the combined effects of various factors on well-performance parameters [7–9]. The use of such methods offers opportunities for developing empirical models suitable for integration into digital field-development management systems and for automating well-condition monitoring.

The pressure gradient in the wellbore of gas–liquid wells is affected by a complex set of factors, including gas production rate, gas and liquid densities, condensate–gas and water–gas ratios, production-tubing length, the wellbore temperature profile, the distance from the tubing shoe to the perforated interval, the thickness of the completed interval, and the gas velocity at the tubing shoe [1,2,5,6].

In the present study, methods of mathematical statistics were used to determine the pressure gradient in the production-tubing string of wells operating with liquid entrainment (water and condensate). The study was based on the results of gas-dynamic well tests involving downhole pressure measurements performed with electronic pressure gauges.

RESEARCH METHODOLOGY AND RESULTS.

To determine the pressure gradient and bottomhole pressure in the wellbore of gas–liquid wells, methods of mathematical statistics based on multiple regression analysis were applied.

The source database comprised the results of gas-dynamic well tests obtained from downhole pressure measurements using electronic pressure gauges. The analysis included data from wells operating with liquid entrainment (water and condensate) at a water–gas ratio (WGR) of at least 1 cm^3/m^3.

Based on the analysis of experimental data and the application of linear regression, an empirical correlation was derived for determining bottomhole pressure while accounting for the principal geological, engineering, and operating parameters of the well. The proposed approach improves the accuracy of pressure calculations under gas–liquid-flow conditions and may be used to analyze and optimize well operating modes.

Table 1 presents the data obtained from these investigations. At the first stage, the source data were systematized and preprocessed.

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The following variables, which characterize well operating conditions and fluid properties, were considered as independent variables: gas production rate (Q_g); condensate–gas ratio (CGR); water–gas ratio (WGR); water density (ρ_w); gas relative density ($\bar{\rho}_g$); ratio of static pressure to wellhead pressure (P_{st}/P_{wh}); average wellbore temperature (T_{avg}); production-tubing length (L_{tub}); distance from the tubing shoe to the uppermost perforation (h_{tub}); gas velocity at the tubing shoe ($V_{tub,shoe}$); length of the perforated interval (l); and bottomhole pressure (P_{bh}), which was taken as the dependent variable.

To improve the reliability of the results, the original dataset was filtered. Data with extreme parameter values—specifically, WGR ≥ 200 cm³/m³ and CGR ≥ 500 cm³/m³—were excluded from the analysis. This ensured greater homogeneity of the statistical sample and improved model stability.

The data were processed using multiple linear regression, which made it possible to establish a quantitative relationship between bottomhole pressure and the combined set of governing factors.

As a result, the following empirical equation was obtained for determining bottomhole pressure:

$$P_{bh} = -113.131 + 0.000785Q_g - 0.06496\text{CGR} - 0.014501\text{WGR} - 0.81683\rho_w - 1.55137(P_{st}/P_{wh}) + 284.3685\bar{\rho}_g + 0.151057T_{avg} - 0.01402L_{tub} - 0.07703h_{tub} - 14.2639V_{tub,shoe} + 0.002707l. \quad (1)$$

The resulting correlation accounts for both the technological parameters of well operation and the physicochemical properties of the fluids, thereby providing a more accurate description of two-phase (gas–liquid) flow conditions in the wellbore.

Analysis of the coefficients in Equation (1) shows that bottomhole pressure is most strongly affected by the gas relative density, the ratio of static pressure to wellhead pressure, and the gas velocity at the tubing shoe. The water–gas and condensate–gas ratios, which characterize the liquid-phase content of the flow, also exert a substantial influence.

To evaluate the applicability of the developed model, the calculated bottomhole-pressure values were compared with those obtained using existing methods. The comparative analysis showed that the proposed correlation provides closer agreement with actual measurements, particularly when the flow contains a substantial liquid phase.

RESULTS AND DISCUSSION.

A comparison of bottomhole-pressure calculations obtained using the developed model and the conventional method [2] is presented in Figure 1.

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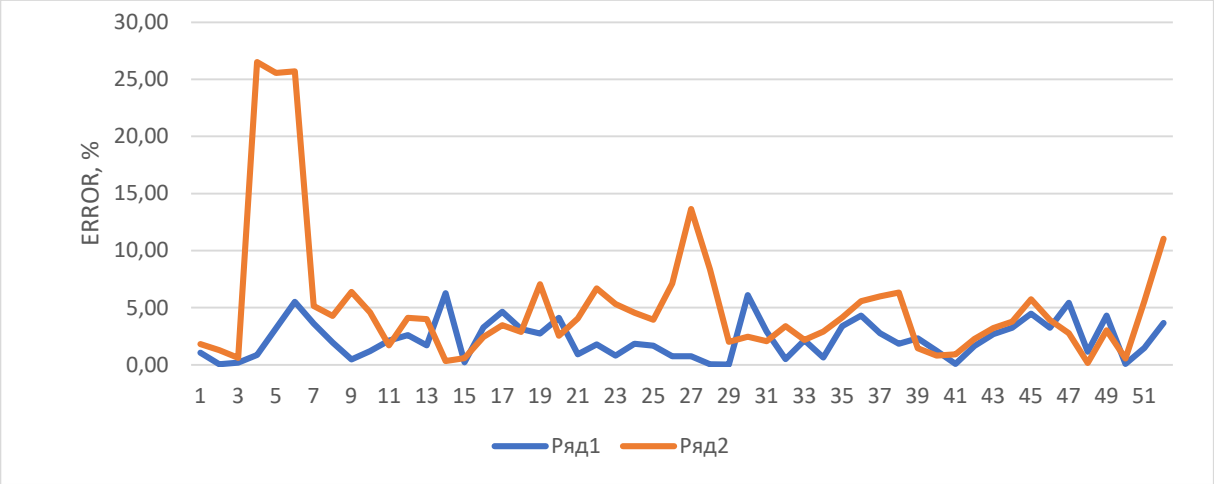


Fig. 1 - Comparison of bottomhole pressures calculated using the linear regression model and the method described in [2]

Error determined for the calculation performed using linear regression

Error determined for the calculation performed according to the procedure described in [2].

To assess the calculation accuracy, the root-mean-square deviation was calculated in accordance with [9,10] using the following equation, with the mean value replaced by the measured value:

$$"S"" = "\sqrt{\frac{\sum_{i=1}^{n}("P"_{meas}" - ""P"_{calc})^2}{"n-1"}}$$

where n is the number of measurements.

The results are presented in Table 2.

Table 1.

Initial data for the calculation and results of the calculation of the pressure in the wellbore operated with gas-liquid flows

Field, well	$P_{bh,meas}$,	Q_g, m³/d	CGR,	WGR,	ρ_w,	P_{st}/P_{wh}	Relative gas	T_{avg}, K	L_{tub}	h_{tub},	$V_{sh,tub}$,	l	$P_{bh,calc}$, regression,	Error, %	$P_{bh,calc}$,	Error, %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
West Kukcha 2	78.44	38207	20.10	0.00	0.00	1.10	0.6177	338.6	2072.29	9.85	2.22	41	79.28	-1.06	79.87	1.82
	77.55	51894	18.50	4.16	1.005	1.14	0.6177	339.6	2072.29	9.85	3.05	41	77.59	-0.06	78.55	1.29

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	76.67	58065	16.53	4.41	1.005	1.17	0.6177	340.1	2072.29	9.85	3.46	41	76.82	-0.20	77.13	0.60
Kalandar 1	81.04	28689	14.08	0.00	0.00	2.09	0.6196	334.1	2076.15	2.85	1.57	51	80.35	0.85	59.55	26.52
	75.08	34973	94.36	51.47	1.025	2.25	0.6196	335.1	2076.15	2.85	2.07	51	72.67	3.20	55.89	25.56
	67.57	38510	51.93	75.31	1.025	2.53	0.6196	335.6	2076.15	2.85	2.56	51	71.30	-5.52	50.21	25.69
Chandyr 19	86.62	69121	5.90	3.12	1.003	1.06	0.6152	339.4	2063.15	14.85	3.59	57	83.49	3.61	91.08	5.15
	86.17	101109	5.54	3.96	1.003	1.12	0.6152	340.4	2063.15	14.85	5.28	57	84.49	1.96	89.86	4.28
	85.32	133582	3.53	3.83	1.003	1.18	0.6152	341.9	2063.15	14.85	7.06	57	84.91	0.48	90.77	6.39
Chandyr 3	86.73	76342	3.51	3.96	1.035	1.21	0.6184	340.9	2080.25	2.75	3.95	40	85.68	1.21	90.71	4.59
	80.76	72397	5.69	12.18	1.035	1.39	0.6184	341.9	2080.25	2.75	3.95	40	82.48	-2.12	79.38	1.71
	80.9	98244	2.36	6.08	1.035	1.36	0.6184	342.9	2080.25	2.75	5.36	40	83.01	-2.60	84.23	4.12
	88.42	91310	5.78	6.31	1.035	1.22	0.6184	340.9	2080.25	2.75	4.68	40	86.91	1.71	91.95	3.99
Alat 1	101.11	44524	5.39	4.31	1.02	1.11	0.6498	345.14	2177.8	28.9	2.00	77.6	94.76	6.28	101.46	0.35
	94.93	66877	8.97	7.18	1.02	1.22	0.6498	345.64	2177.8	28.9	3.22	77.6	94.72	0.23	94.37	0.59

Continuation of Table 1.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

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Alat	88.71	82768	9.28	5.80	1.02	1.36	0.6498	346.14	2177.8	28.9	4.30	77.6	91.61	-3.26	86.54	2.45
	84.58	95935	8.76	6.25	1.02	1.49	0.6498	346.64	2177.8	28.9	5.23	77.6	88.52	-4.66	81.64	3.48
	89.41	82966	9.26	5.79	1.02	1.36	0.6498	346.64	2177.8	28.9	4.27	77.6	92.22	-3.14	86.82	2.90
Xisha, 1104	63.19	35631	2.02	9.43	1.007	1.18	0.6299	292.5	2395.9	29.8	2.68	36.5	61.45	2.75	58.73	7.06
	64.54	17398	1.38	9.66	1.007	1.08	0.6299	291.5	2395.9	29.8	1.28	36.5	67.19	-4.11	62.89	2.56
	63.72	26819	1.79	9.84	1.007	1.12	0.6299	292	2395.9	29.8	2.00	36.5	64.31	-0.92	61.13	4.06
	62.95	33968	2.12	9.89	1.007	1.18	0.6299	292.5	2395.9	29.8	2.57	36.5	61.81	1.80	58.74	6.69
	63.81	26243	1.37	7.32	1.007	1.13	0.6299	291	2395.9	29.8	1.96	36.5	64.33	-0.81	60.41	5.33
Xisha, 1102	72.31	39511	1.09	18.83	1.006	1.10	0.6299	359.9	2395.9	61.1	2.61	63	73.64	-1.85	69.01	4.56
	72.67	37497	3.52	9.92	1.006	1.09	0.6299	360.1	2395.9	61.1	2.47	63	73.90	-1.69	69.8	3.95

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	72.03	4948 0	3.88	13.58	1.0066	1.16	0.6299	359.8	2395.9	61.1	3.29	63	71.48	0.76	66.9	7.12
	71.5	5084 6	2.83	27.85	1.0066	1.27	0.6299	359.5	2395.9	61.1	3.41	63	70.95	0.76	61.74	13.65
	71.66	4634 0	4.66	16.06	1.0066	1.17	0.6299	359.6	2395.9	61.1	3.10	63	71.70	-0.06	65.67	8.36
Xiji, 1	68.37	4758 0	7.57	10.09	1.0188	1.14	0.62	350.45	2362.3	18.7	3.35	54	68.40	-0.05	66.99	2.02
	70.55	1921 7	6.24	5.93	1.0188	1.08	0.62	347.45	2362.3	18.7	1.31	54	74.87	-6.12	68.81	2.47
	70.48	3269 2	7.34	8.81	1.0188	1.09	0.62	348.95	2362.3	18.7	2.23	54	72.53	-2.90	69.02	2.07
	69.52	4333 2	8.31	13.29	1.0188	1.13	0.62	348.95	2362.3	18.7	2.99	54	69.87	-0.50	67.16	3.39
	68.76	5406 7	7.99	12.43	1.0188	1.17	0.62	350.45	2362.3	18.7	3.78	54	67.28	2.15	67.25	2.20
	69.13	4374 3	8.78	13.72	1.0188	1.14	0.62	349.45	2362.3	18.7	3.04	54	69.58	-0.65	67.12	2.91
Xisha, 1	57.76	2891 5	1.66	1.66	1.005	1.32	0.6284	336.42	2326.9	125.3	2.40	31	59.72	-3.39	55.37	4.14

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	57.3	33264	5.80	1.44	1.005	0.00	0.6284	338.42	2326.9	125.3	2.78	31	59.77	-4.31	54.11	5.57

Table 1 (continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Xisha, 1	57.2	38134	7.84	15.03	1.005	1.30	0.6284	337.42	2326.9	125.3	3.19	31	55.62	2.77	53.77	6.00
	57.39	30134	7.17	3.98	1.005	1.30	0.6284	334.42	2326.9	125.3	2.51	31	58.44	-1.83	53.76	6.33
Chandyr, 5	74.5	71385	4.15	5.04	1.002	1.09	0.6157	339.255	2109	-18	4.36	32	76.23	-2.32	75.59	1.46
	74.36	81496	3.78	5.20	1.002	1.12	0.6157	339.755	2109	-18	4.99	32	75.27	-1.23	74.97	0.82
	73.98	89731	4.10	5.35	1.002	1.15	0.6157	338.755	2109	-18	5.52	32	73.91	0.09	74.66	0.92
Xisha, 1103	77.61	27436	2.62	7.00	1.01	1.23	0.6351	342.7	2416.8	57.2	1.65	40	76.32	1.66	75.84	2.28
	77.17	45116	4.26	15.96	1.01	1.27	0.6351	344.7	2416.8	57.2	2.73	40	75.09	2.70	74.68	3.23
	74.92	60869	3.94	19.71	1.01	1.34	0.6351	346.7	2416.8	57.2	3.79	40	72.48	3.26	72.09	3.78
	72.32	70257	4.10	22.20	1.01	1.46	0.6351	347.2	2416.8	57.2	4.54	40	69.08	4.48	68.16	5.75

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	73.5	58309	4.12	22.64	1.01	1.37	0.6351	346.7	2416.8	57.2	3.75	40	71.12	3.24	70.61	3.93
Chandyr, 12	100.17	86470	9.01	3.40	1.003	1.06	0.6099	342.84	2080.25	-23.25	3.86	75	94.71	5.45	102.95	2.78
	99.77	128289	6.56	3.83	1.003	1.11	0.6099	343.84	2080.25	-23.25	5.75	75	100.91	-1.14	99.94	0.17
	99	151832	9.58	5.86	1.003	1.18	0.6099	343.84	2080.25	-23.25	6.86	75	103.26	-4.30	96.01	3.02
Chandyr, 17	76.76	62616	6.64	2.68	1.002	1.04	0.6163	335.4	2063.19	10.81	3.70	63	76.83	-0.09	76.33	0.56
	77.01	89472	5.36	8.99	1.002	1.11	0.6163	337.1	2063.19	10.81	5.26	63	75.87	1.48	72.71	5.58
	76.56	112759	4.26	11.62	1.002	1.22	0.6163	335.7	2063.19	10.81	6.68	63	73.75	3.67	68.1	11.05

Table 2

Error in Bottomhole Pressure Determination

Metric	According to Method [1]	Regression Model
Minimum, %	0.17	0.05
Maximum, %	26.52	6.28
Mean, %	5.14	2.26
RMSD, %	5.78	2.27

Additional statistics: $R^2 = 0.96$; $F_{calc} = 84.30$; $F_{tab} = 2.04$

The analysis demonstrates that the regression model reduces the mean error by more than a factor of two and the root-mean-square deviation (RMSD) by a factor of 2.6. Furthermore, the number of cases with an error exceeding 5% is significantly reduced.

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Under certain well operating conditions, deviations are observed due to liquid accumulation. For Well No. 1 at the Alat field (Fig. 2), a liquid column was identified above the downhole gauge.

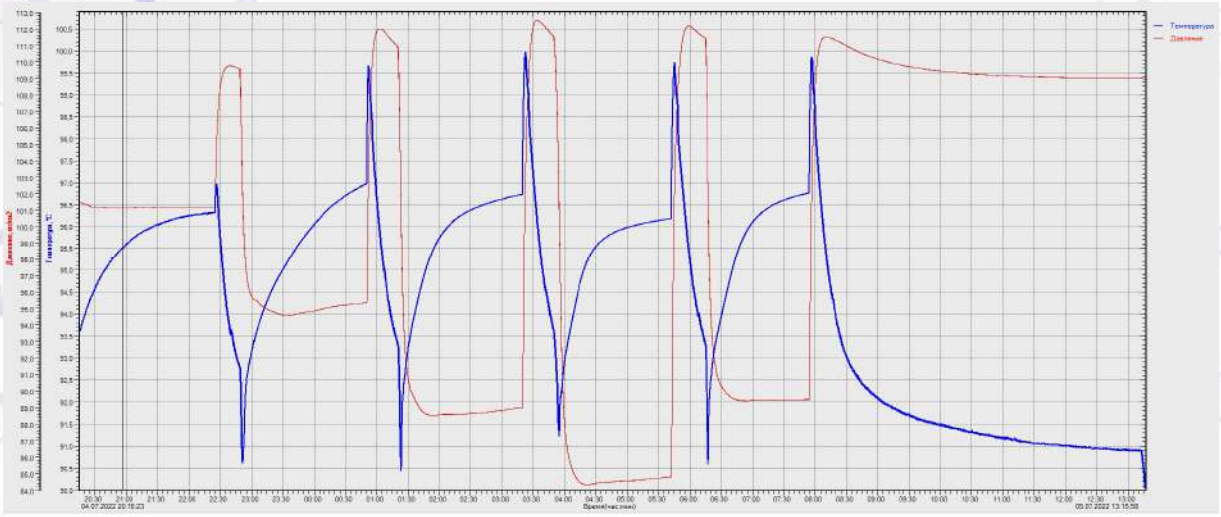


Fig. 2. Variation in downhole pressure-gauge readings at a depth of 2,245.48 m in the Alat-1 well (6 mm, 8 mm, 10 mm, 12 mm, 10 mm, and pressure buildup test)

It was established that an insufficient gas flow rate results in incomplete liquid removal, thereby affecting calculation accuracy. Additional analysis [11,12,13] (Fig. 3) confirms the influence of hydrodynamic conditions.

When the ratio of the calculated pressure gradient to the pressure gradient attributable to the weight of the gas column ranges from 1.01 to 1.09, the error is 5.45–6.12%.

Thus, the developed calculation equation provides higher accuracy in determining bottomhole pressure under gas–liquid flow conditions and can be used to optimize well operating modes and support the digitalization of field-development processes.

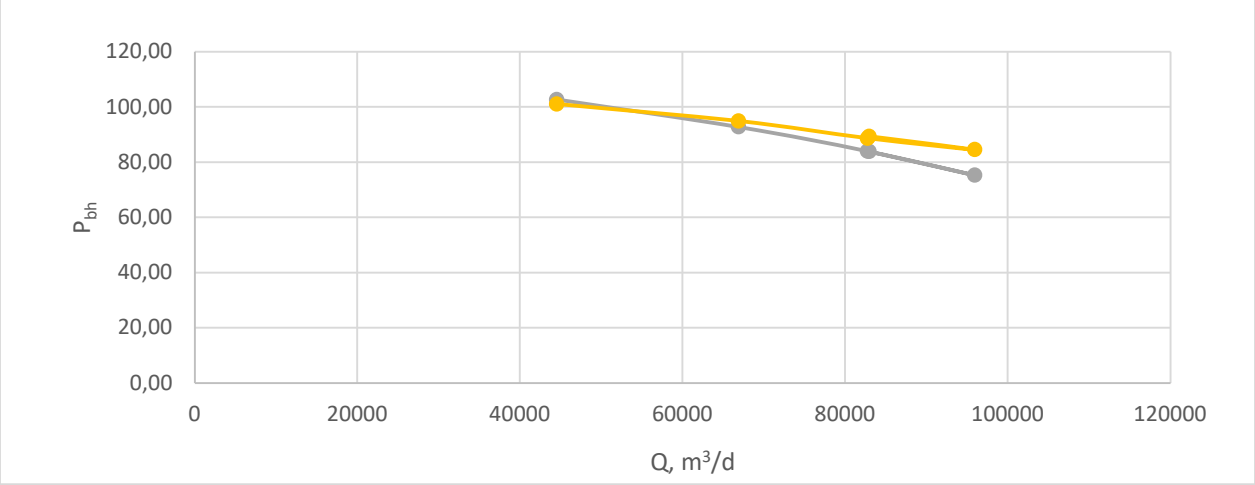


Fig. 3. Well indicator diagram; *yellow line*—indicator curve, *gray line*—characteristic curve

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Scientific novelty: The following new scientific findings were obtained in this study:

– a regression-based calculation equation was developed for determining bottomhole pressure in gas–liquid wells, accounting for the combined effects of the technological and physicochemical parameters of well operation;

– quantitative relationships were established for the effects of the water–gas ratio, condensate–gas ratio, and tubing-string parameters on the pressure gradient under two-phase flow conditions;

– the feasibility of applying mathematical statistics to improve the accuracy of bottomhole-pressure calculations for wells operating with liquid carryover was substantiated;

– the conditions associated with increased calculation error were identified, specifically liquid accumulation in the wellbore and an insufficient liquid-lifting velocity;

– it was demonstrated that the proposed calculation equation substantially reduces the error in bottomhole-pressure determination compared with standard methods.

CONCLUSIONS: It was established that the use of standard methods for calculating bottomhole pressure under gas–liquid flow conditions results in substantial errors, particularly when the liquid-phase content is significant.

A calculation equation based on multiple linear regression was developed for determining bottomhole pressure. The equation accounts for the principal well-operating parameters, including gas flow rate, water–gas ratio, condensate–gas ratio, and tubing-string characteristics.

The proposed calculation equation was shown to provide higher accuracy than the conventional method: the mean error was reduced by more than a factor of two, while the root-mean-square deviation was reduced by a factor of 2.6.

The relative gas density, the ratio of static pressure to wellhead pressure, and the gas velocity at the tubing shoe were found to have the greatest effect on the accuracy of bottomhole-pressure determination.

The increase in calculation error is associated with liquid accumulation in the wellbore at an insufficient gas-flow velocity, as confirmed by the results of downhole measurements.

The statistical significance of the developed calculation equation is confirmed by the high coefficient of determination ($R^2 = 0.96$) and by the calculated Fisher criterion exceeding its tabulated value.

The proposed calculation equation can be used to interpret gas-hydrodynamic well-test data, optimize well operating modes, and develop digital systems for monitoring and managing gas and gas-condensate field development.

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