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MOISTURE CONTENT OF NATURAL GAS IN BOTTOM HOLE ZONE

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For the traditional problem of gas flow to a well in the center of circular reservoir, the influence of initial reservoir conditions on dynamics of gas moisture content distribution has been determined. Investigations have been performed in the framework of mathematical model of non-isothermal real gas flow through porous media where heat conductivity was considered to be negligible in comparison with convective heat transfer. It is closed by empirical correlation of compressibility coefficient with pressure and temperature, checked in previous publications. Functional dependence of moisture content in gas on pressure and temperature is based on empirical modification of Bukacek relation. Numerical experiment was performed in the following way. At first step, axisymmetric problem of non-isothermal flow of real gas in porous media was solved for a given value of pressure at the borehole bottom, which gives the values of pressure and temperature as functions of time and radial coordinate. Conditions at the outer boundary of the reservoir correspond to water drive regime of gas production. At the second step, the calculated functions of time and coordinate were used to find the analogous function for moisture content. The results of experiment show that if reservoir temperature essentially exceeds gas – hydrate equilibrium temperature than moisture content in gas distribution is practically reflects the one of gas temperature. In the opposite case, gas will contain water vapor only near bottom hole and at the rest of reservoir it will be almost zero. In both cases, pressure manifests its role through the rate of gas production, which in turn influences convective heat transfer and gas cooling due to throttle effect.

***Key words*:** moisture content of natural gas; non-isothermal flow; gas hydrates; numerical experiment

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Introduction. A recent publication by the authors [1] describes the peculiarities of natural gas production in the Arctic zone of Russia, which must be taken into account whereas mathematical modeling of relevant technological processes is considered. The paper also gave numerous examples of calculating the formation of gas hydrates in wells and gas pipelines. This publication is supplemented the article [1] by analyzing the dynamics of temperature and pressure in the bottom hole of gas wells and gives an assessment of these technological parameters' effect on the moisture content of the produced gas. The relevance of solving such a problem is determined by reservoir water influence on hydrate formation in the bottom hole zone, as well as by the need to dry gas before its delivery to gas pipeline. In addition, with the current practice of pumping methanol or other inhibitors into wells, in order to prevent hydrate formation directly in the gas-bearing formation, it is necessary to calculate the flow rate of this reagent.

Equilibrium moisture content of natural gas. In gas and gas-condensate fields gas contacts with residual reservoir water with boundary and underlying waters and, therefore, contains water vapor. Under conditions of thermodynamic equilibrium, their maximum amount depends on pressure, temperature and gas composition [3-5, 7, 9]. It is called the moisture content w and in thermodynamics is defined as the ratio of the mass of water vapor $m_{\mathrm{H_2O}}$ to the mass of dry gas m_{g}. In engineering calculations in Russia, due to imitation of US translated reference books, moisture content refers to the ratio of the water vapor mass to the standard volume of dry gas W in kilograms per 1000 m^3.

The analytical dependences of the moisture content of natural gases W on pressure p in pascals and temperature T are modifications of the Bukacek formula [13]:

$$W = \frac{A(T)}{p} + B(T), \tag{1}$$

where A is a coefficient equals to moisture capacity (moisture content under saturation conditions) of an ideal gas at normal atmospheric pressure; B – correction for imperfection of natural gas, depending on the gas composition [4, 7].

We will opt for the ratios proposed in monographs [3, 4] as the most commonly used:

$$WG(p,T)=10^{-3}\left(\frac{0.457}{p}\exp\left(0.0735\,(T-273.15)-0.00027\,(T-273.15)^2\right)\right)+$$

$$+0.0418\exp\left(0.054\,(T-273.15)-0.0002\,(T-273.15)^2\right); \qquad (2)$$

$$WB(p,T)=0.016\cdot10^{-3}\left(\frac{0.1\,ps(T)}{p}47482+10^{-\frac{1713.3}{T}+6.694}\right), \qquad (3)$$

where $ps(T)=0.0061038\exp\left(0.0735(T-273.15)-0.00027(T-273.15)^2\right)$ – water vapor pressure above pure water.

Relations (2), (3) are recommended to be used for natural gases with a relative air density of 0.6. Their identity is demonstrated in Figure 1. In further calculations, formula (3) was used, since it is easily modified when it is necessary to calculate the pressure of water vapor in the gas equilibrious with hydrate. In this case, instead of the function above, corresponding empirical relation should be used, for which the formula proposed in [4] is chosen

$$p^{\mathrm{h}}_{\mathrm{H_2O}}(p,T)=\exp\left(29.396-\frac{6234.874}{T}-0.1593\ln(p)\right). \qquad (4)$$

Dynamics of moisture content in the bottom hole of gas wells. The moisture content, according to relation (3), is a function of pressure and temperature. Consequently, in order to determine its distribution in the bottom hole zone, it is necessary to solve the problem of non-isothermal filtration of real gas with appropriate boundary and initial conditions.

For a mathematical description of gas production from a single well located in the center of a circular reservoir, the system of equations describing non-isothermal flow of real gas in a porous medium is used, in which energy transfer due to heat conduction is considered negligible compared to convective transfer [2, 11, 12]. Dimensionless form of corresponding equations can be reduced to two equations for gas pressure and gas temperature:

$$\frac{\partial}{\partial \bar t}\left(\frac{\bar p}{Z\bar T}\right)=\frac{1}{\bar r}\frac{\partial}{\partial \bar r}\left(\bar r\frac{\bar p}{Z\bar T}\frac{\partial \bar p}{\partial \bar r}\right),\ \bar r_{\mathrm{b}}<\bar r<\bar r_{\mathrm{k}},\ \bar t>0; \qquad (5)$$

$$\frac{\partial \bar T}{\partial \bar t}=\left(1+\frac{\bar T}{Z}\frac{\partial Z}{\partial \bar T}\right)\frac{\partial \bar p}{\partial \bar t}+\frac{c_p}{R}\frac{\bar p}{Z\bar T}\frac{\partial \bar T}{\partial \bar r}\frac{\partial \bar p}{\partial \bar r}-\frac{\bar T}{Z}\frac{\partial Z}{\partial \bar T}\left(\frac{\partial \bar p}{\partial \bar r}\right)^2,\ \bar r_{\mathrm{b}}<\bar r<\bar r_{\mathrm{k}},\ \bar t>0; \qquad (6)$$

where $\bar t=\kappa_p t/l^2$; $\bar p=p/p_0$; $\bar T=c_{\mathrm{r}}T/mp_0$; $\bar r=r/l$; $\bar r_{\mathrm{b}}=r_{\mathrm{b}}/l$; $\bar r_{\mathrm{k}}=r_{\mathrm{k}}/l$; c_p – specific heat of gas at constant pressure; c_{r} – volumetric heat capacity of the gas-saturated porous medium; k – permeability coefficient; l – characteristic size; m – porosity; p – pressure; R – gas constant; r – radial coordnate; r_{b} – outer well radius; r_{k} – formation contour radius; T – temperature; t – time; Z – gas imperfection coefficient; $\kappa_p=kp_0/m\eta$ – piezoconductivity coefficient of gas-saturated porous medium; η – dynamic viscosity of gas; subscript «0» corre-

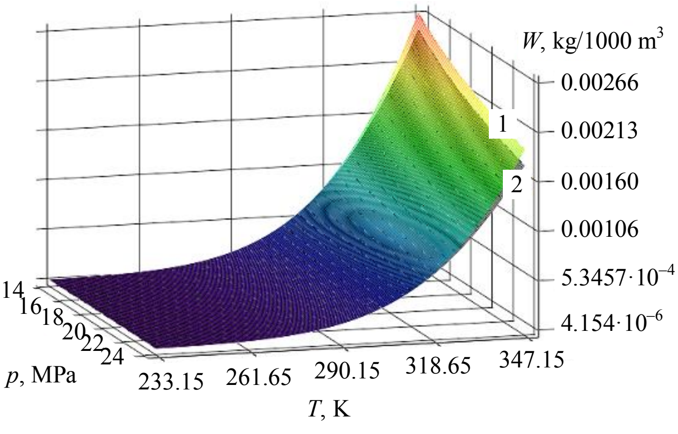

Fig.1. Dependence of the moisture content of natural gas on temperature and pressure. Surface 1 is constructed according to formula (3), surface 2 – to formula (2)

sponds to the initial state of the gas-bearing formation. In the rest of paper bar above the dimensionless variables is omitted for convenience.

In paper [10] it was shown that the production at constant bottom hole pressure is most favorable, since it provides a more even pressure distribution than at constant mass flow rate. Thus, a constant gas pressure is set at the bottom hole

$$p = p_{\mathrm{b}}; \quad r = r_{\mathrm{b}}. \tag{7}$$

Conditions, which simulate the absence of gas and heat flows, are set on the reservoir boundary, which corresponds to the water drive regime:

$$\frac{\partial p}{\partial r} = 0; \quad \frac{\partial T}{\partial r} = 0; \quad r = r_{\mathrm{k}}. \tag{8}$$

At the initial moment pressure and temperature are considered constant:

$$p(r,0) = 1; \quad T(r,0) = T_0; \quad r_{\mathrm{b}} \le r \le r_{\mathrm{k}}. \tag{9}$$

It should be noted that in this formulation, the gas temperature at the bottom hole ($r = r_{\mathrm{b}}$) is considered determined during the solution of the problem, and equation (6) is a first-order quasilinear hyperbolic equation. The characteristics of this equation go beyond the right boundary, therefore the boundary condition for the absence of heat flux (8) is sufficient to determine its only solution.

As the equation of state, the Latonov – Gurevich equation is taken [8]

$$\mathrm{Z} = \left(0.17376\ln\left(\frac{mp_0}{c_{\mathrm{r}}T_{\mathrm{c}}}T\right) + 0.73\right)^{\frac{p_0}{p_{\mathrm{c}}}p} + 0.1\frac{p_0}{p_{\mathrm{c}}}p, \tag{10}$$

where the subscript «c» corresponds to the critical state of natural gas, which is a mixture of gases, mainly of the paraffin series, starting with methane.

The critical pressure and temperature of the gas mixture are determined according to Kay's rule [14]:

$$p_{\mathrm{c}} = \sum_{i=1}^{n} y_i p_{\mathrm{c}i}; \; T_{\mathrm{c}} = \sum_{i=1}^{n} y_i T_{\mathrm{c}i},$$

where y_i, $p_{\mathrm{c}i}$, $T_{\mathrm{c}i}$ – volume part, critical pressure and temperature of the *i* component of natural gas.

The gas constant of the gas mixture is determined by the formula

$$R = 8.314/\mu_g,$$

where $\mu_g = \sum_{i=1}^{n} y_i \mu_{gi}$ – molar mass of natural gas; μ_{gi} – molecular weight of *i* component of natural gas.

The calculations were performed at the following values of the parameters corresponding to two fields of the Sakha Republic (Yakutia). 1. Srednevilyuyskoe: R = 449.4 J/(kg·K); p_0 = 24 MPa; T_0 = 323 K; p_{b} = 14 MPa; p_{c} = 4.6596 MPa; T_{c} = 205.022 K; c_p/R = 5.118; c_{r}/mp_0 = 1.234 1/K; a = 7.009 K и b = 178.28 K – constants for calculating the equilibrium temperature of hydrate formation, found by approximation of the thermodynamic equilibrium curve determined by the Sloan method [15] or by the Istomin method [6] with a known gas composition (volume content), %: CH_4 90.34; C_2H_6 4.98; C_3H_8 1.74; iC_4H_{10} 0.22; nC_4H_{10} 0.41; C_5H_{12+} 1.55; CO_2 0.28; N_2 0.48; gas density related to air – 0.634.

2. Otradninskoe: R = 438.3 J/(kg·K); p_0 = 18.835 MPa; T_0 = 286.35 K; p_{b} = 16.87 MPa; p_{c} = 4.471 MPa; T_{c} = 195.376 K; c_p/R = 5.248; c_{r}/mp_0 = 3.539 1/K; a = 6.635 K; b = 182.951 K; gas composition (volume content), %: CH_4 83.15; C_2H_6 4.16; C_3H_8 1.48; iC_4H_{10} 0.17; nC_4H_{10} 0.50;

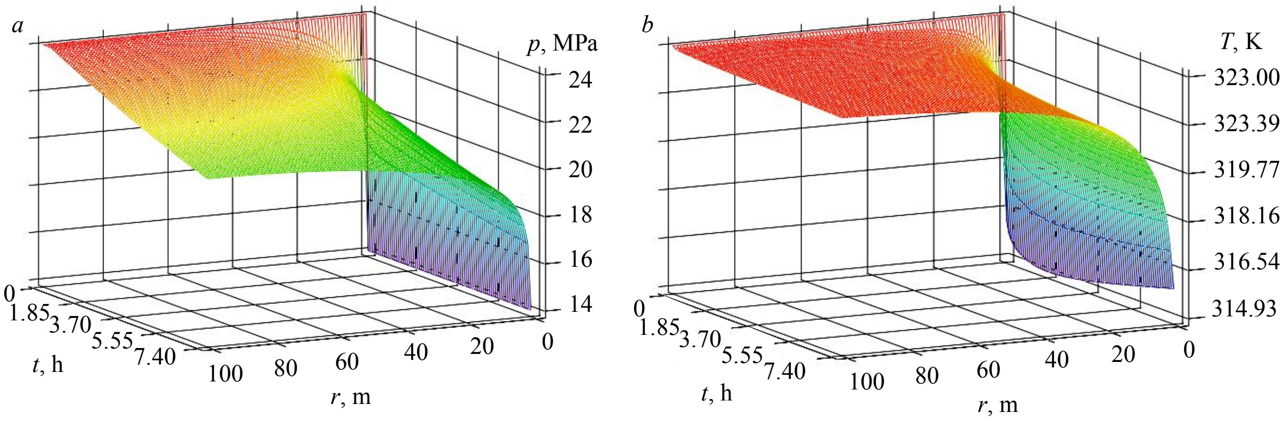

Fig.2. Dynamics of pressure (a) and temperature (b) distribution in the reservoir for the Srednevilyuiskoye field

iC_5H_{12} 0.12; nC_5H_{12} 0.17; C_6H_{14} 0.17; C_7H_{16+} 0.28; CO_2 0.07; N_2 9.50; H_2 0.02; He 0.21; gas density related to air – 0.685.

It can be seen that at approximately equal depth of the productive formation, the composition of natural gas, as well as the reservoir conditions of these fields, are significantly different. The hydrate formation temperature calculated by the formula for given bottom hole pressures is 293.6 K and 293.4 K for the Srednevilyuyskoe and Otradninskoe fields, respectively. Thus, in the second case, gas production will lead to formation of hydrates in the bottom hole zone, since the initial temperature of the reservoir is below the equilibrium temperature of hydrate formation. It is also worth noting that for the indicated values of the relative density of gases, the correction coefficient to formulas (2) and (3) is equal to 0.99, i.e. it can be ignored in subsequent calculations.

Analysis of the calculations' results starts with Srednevilyuyskoe field. It should be noted that for the given values of the input data, the duration of transient processes of pressure and temperature changes is several hours, so here the results of calculations corresponding to this period are presented. Figure 2 presents the dependences of the gas temperature and pressure on time and the radial coordinate.

These data were used to calculate a similar dependence of the gas moisture content using the formula

$$w(r,t)=\frac{W(p,T)}{\rho(p,T)},$$

where ρ – gas density.

The results of the calculations are presented in Fig.3. It can be seen that the content of water vapor in the gas is very small, and the shape of the surface $w(r,t)$ is almost identical to the surface $T(r,t)$. Therefore, in the case of gas contact with water, its moisture content is mainly determined by the nature of the temperature change. However, one should not forget that these changes depend on the intensity of gas production, i.e. on pressure changes, which in turn, determine the intensity of convective heat transfer and the degree of gas cooling due to throttling.

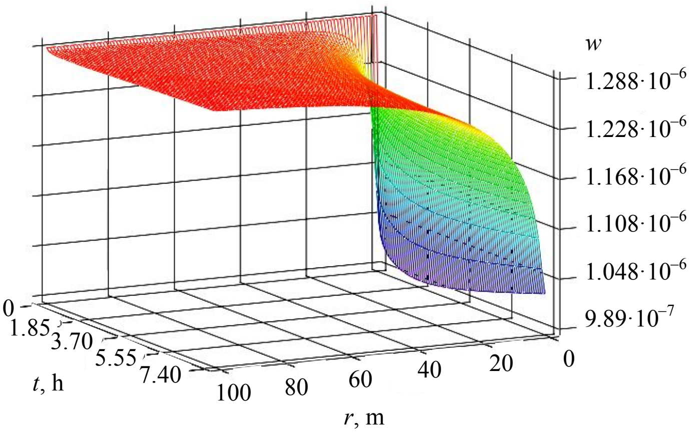

Fig.3. The dynamics of the gas moisture content distribution in the reservoir for Srednevilyuyskoe field

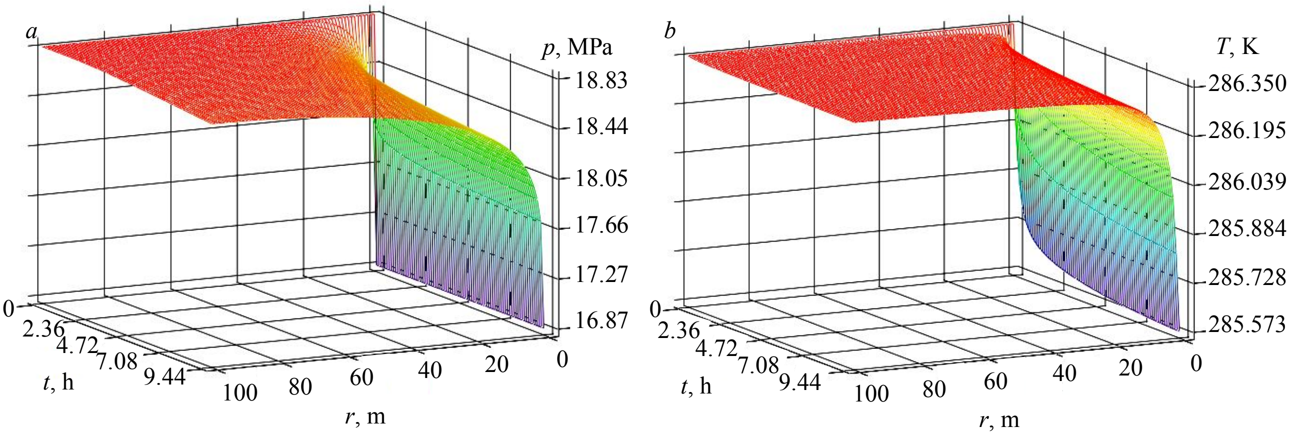

Fig.4. Dynamics of pressure (a) and temperature (b) distribution in the reservoir for the Otradninskoe field

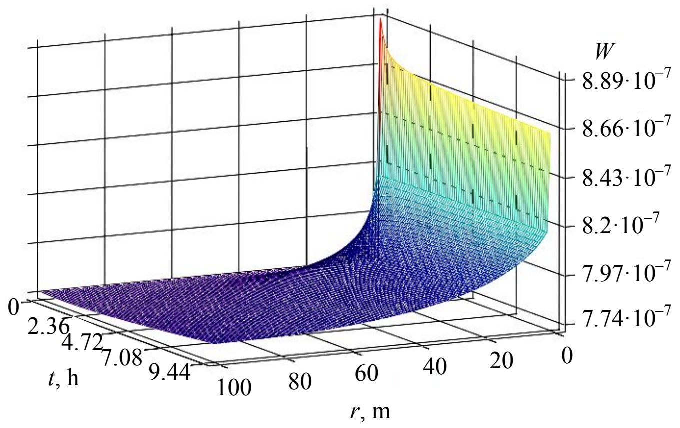

Fig.5. The dynamics of the gas moisture content distribution in the reservoir for Otradninskoe field

The corresponding analysis for the Otradninskoe field gave the following results. Here, the initial gas temperature is below the equilibrium temperature of hydrate formation. Therefore, in formula (3) the expression for the pressure of water vapor over pure water should be replaced by formula (4), which determines the pressure of water vapor above hydrate. In this case, despite the qualitative similarity between the dependences of pressure and temperature on the coordinate and time with the previous example (Fig.4), the surface shape $w(r,t)$is significantly different, and the weight share of moisture in the gas is close in magnitude to the previous result only in the immediate vicinity of the bottom hole and then decreases sharply to almost zero (Fig.5).

Conclusion. In this computational experiment, it was shown that if the reservoir temperature significantly exceeds the equilibrium hydrate formation temperature, the distribution of moisture content in the bottom hole zone will be almost identical to the temperature distribution. Otherwise, the gas will contain water vapor only near the wellbore bottom, and then the moisture content will be almost zero. The role of pressure in both cases is manifested through the intensity of gas production which, in turn, determines the intensity of convective heat transfer and the degree of gas cooling due to throttling.

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REFERENCES

1. Bondarev E.A., Rozhin I.I., Argunova K.K. Features of mathematical modeling of natural gas production and transport systems in the Russia's Arctic zone. *Zapiski Gornogo instituta*. 2017. Vol. 228, p. 705-716. DOI: 10.25515/PMI.2017.6.705 (in Russian).

2. Bondarev E.A., Argunova K.K., Rozhin I.I. Plane-parallel nonisothermal filtration of gas: the role of heat transfer. *Journal of Engineering Physics and Thermophysics*. 2009. Vol. 82. N 6, p. 1073-1079. DOI: 10.1007/s10891-010-0286-6 (in Russian).

3. Brusilovsky A.I. Phase transformations in the development of oil and gas fields. Moscow: Grail, 2002, p. 575 (in Russian).

4. Gukhman L.M. Treatment of the Northern fields gas for long-distance transport. Leningrad: Nedra, 1980, p. 161 (in Russian).

5. Degtyarev B.V., Bukhgalter E.B. Countering hydrates in gas wells in the Northern regions. Moscow: Nedra, 1976, p. 197 (in Russian).

6. Istomin V.A., Kwon V.G. Prevention and elimination of gas hydrates in gas production systems. Moscow: OOO «IRTs Gazprom», 2004, p. 506 (in Russian).

7. Korotaev Yu.P., Kuliev A.M., Musayev R.M. Countering hydrates in natural gas transport systems. Moscow: Nedra, 1973, p. 136 (in Russian).

8. Latonov V.V., Gurevich G.R. Calculation of the compressibility of natural gases. *Gazovaya promyshlennost'*. 1969. N 2, p. 7-9 (in Russian).

9. Namiot A.Yu. Solubility of gases in water: A Guidebook. Moscow: Nedra, 1991, p. 167 (in Russian).

10. Nikolaev V.E. Numerical analysis of interaction of thermal and hydrodynamic processes at gas filtration. The autor ... Candidate of Physics and Mathematics. Yakutskii gosudarstvennyi universitet im. M.K.Ammosova. Yakutsk, 2000, p. 109 (in Russian).

11. Bondarev E.A., Vasil'ev V.I., Voevodin A.F., Pavlov N.N., Shadrina A.P. Thermohydrodynamics of gas production and transport systems. Novosibirsk: Nauka, Sibirskoe otdelenie, 1988, p. 272 (in Russian).

12. Bondarev E.A., Argunova K.K., Rozhin I.I. Plane-parallel nonisothermal gas filtration: the role of thermodynamics. *Journal of Engineering Thermophysics*. 2009. Vol. 18. N 2, p. 168-176. DOI: 10.1134/S1810232809020088.

13. Bukacek R.F. Equilibrium moisture content of natural gases. *Research Bulletin*. Institute of Gas Technology, Chicago, USA. 1955. Vol. 8. N 11, p. 20.

14. Kay W.B. Density of hydrocarbon gases and vapors at high temperature and pressures. *Industrial & Engineering Chemistry Research*. 1936. Vol. 28, p. 1014-1019.

15. Sloan E.D., Koh C.A. Clathrate hydrates of natural gases. Boca Raton: Taylor & Francis Group/CRC Press, 2008, p. 720.

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