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Some Aspects Concerning the Interpretation of a Gas Reservoir Performance from Production and Pressure Data

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Abstract

The flow generated by the system of gas producing wells is reflected within a zero-dimensional model by the time variations of the average reservoir pressures and cumulative fluid productions. Although the use of the zero-dimensional models corresponding to the gas reservoirs seems to be simple, in order to avoid committing serious errors, special attention has to be paid to the evaluations of gas cumulative production, average reservoir pressure and water cumulative influx. This paper includes three case studies which illustrate the above mentioned aspects.

Key words: *gas reservoir, zero-dimensional models, material balance equation, cumulative gas production*

Basic Considerations

Taking into account the fact that, into the reservoir, the gas contains water vapors and condensate, as well as the fact that these fluids are produced through the wells altogether with the gas, it is necessary that the cumulative gas production G_p in the material balance equation should be written as

$$\frac{G_p}{G} = 1 - \frac{b_{gi}}{b_g}\left(1 - \frac{W_e - b_w W_p}{G\, b_{gi}}\right), \tag{1}$$

which also includes the condensate and water vapors [2, 5].

In the case of gas reservoirs having reservoir rocks of very low permeability, the fact that the average reservoir pressure might be inexactly estimated if the respective estimation is not based on well pressure buildup data has to be taken into account.

The calculation of the cumulative water influx also involves special aspects, caused by the long delay with which pressure drops from wells reach the initial gas–water contact. A major error is committed if accepting that the pressure decline at the initial gas–water contact is the same with the reservoir average pressure decline. The reservoirs having pressures higher than the litostatic pressure are associated with the rock compaction phenomenon, which induces certain abnormal behaviors in the zero-dimensional model described by equation (1).

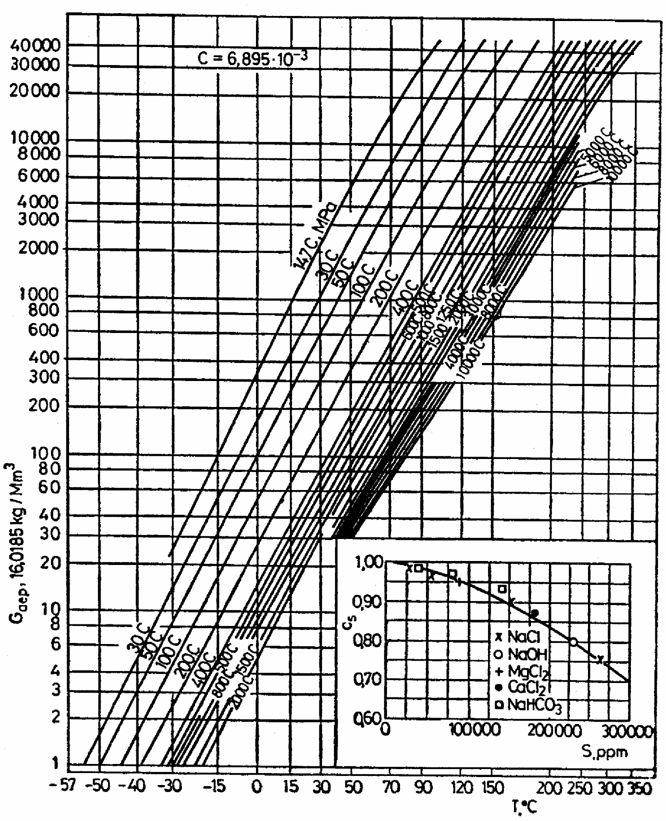

Figure 1. The water content of natural gas in the presence of liquid water

If the gas reservoir behavior is volumetric, the cumulative water influx W_e is null, and if the cumulative water production W_p is negligible, equation (1) is reduced to the form

$$\frac{G_p}{G} = 1 - \frac{b_{gi}}{b_g}, \tag{2}$$

where the cumulative gas production G_p has to include the dry gas production (from the separator), the condensed production converted into an equivalent gas volume, the production of water being in vapor state in the reservoir, and the production of gas ventilated at the condensed tank.

Taking into consideration that the natural gas in the gas reservoir was in contact with the interstitial water for billions of years, we suppose that this gas is saturated with water vapors. In stock-tank conditions, a part of these vapors condensate and are separated from gas as liquid water. The water content of the natural gas in the presence of liquid water, for a range of pressure and temperature values, is shown in Figure 1. The main part of the diagram in this figure presents the pure water content, while the plot in the right bottom corner shows the values of the correction coefficients accounting for the effect of the dissolved solids on water content of the gas. Although it seems to be simple, the accurate determination of the water amount, in reservoir conditions, contained by the gas produced by wells, involves some complications. For example, interstitial water can become mobile during reservoir pressure decline, being produced by wells at the same time with the gas. In many cases, the reservoir is in the capillary transition zone state and, consequently, the water saturation is higher than the irreducible saturation, determining the wells to produce interstitial water from the beginning. Care must be taken not to consider this liquid water produced by wells as water originated in the water vapors contained in the reservoir gas.

The produced interstitial water leads to an increase of the pore volume occupied by gas. Consequently, in absence of a water influx (W_e = 0), in equation (1), the gas volume in the reservoir at a given time will be equal to the initial volume occupied by gas in the reservoir plus the produced water volume. On the other hand, the produced interstitial water can be differentiated by the produced vapor–state water, based on the difference between their salt content, knowing that the water resulted from vapor condensation has no salinity.

It can be noticed that, by decreasing the reservoir pressure, the water vapor content in equilibrium state increases. This increase is due to the vaporizing of a part of the interstitial water. Thus, the vaporized interstitial water leads to an increase of the pore volume occupied by gas and it is produced by wells as fresh water. Slider [5] recommends that all the quantity of water produced in excess to the vaporized water content of reservoir gas be considered, in equation (1), as produced water W_p. Even in these conditions, the problem is not rigorously solved, because the difference between the quantity of water produced and the original water-vapor content of the produced gas requires the correction of the pore volume available for gas in the reservoir, as a consequence of the fact that interstitial water vaporizing accompanies the reservoir pressure decline.

Another unimportant error associated to the zero-dimensional model described by equation (1) for $W_e = 0$ refers to the impossibility of taking into consideration the kinetic effect bound to water vaporizing phenomenon. Thus, the time needed to acquire the equilibrium of vapor – water system on each pressure step cannot be known. Moreover, gas production is a continuous process which doesn't allow the achievement of the respective equilibrium on the pressure steps. Another impediment in achieving the system equilibrium is that water, which is present in the least pores, offers an interface of very small area between gas and water. Consequently, establishing water velocity of vaporization remains a very difficult task.

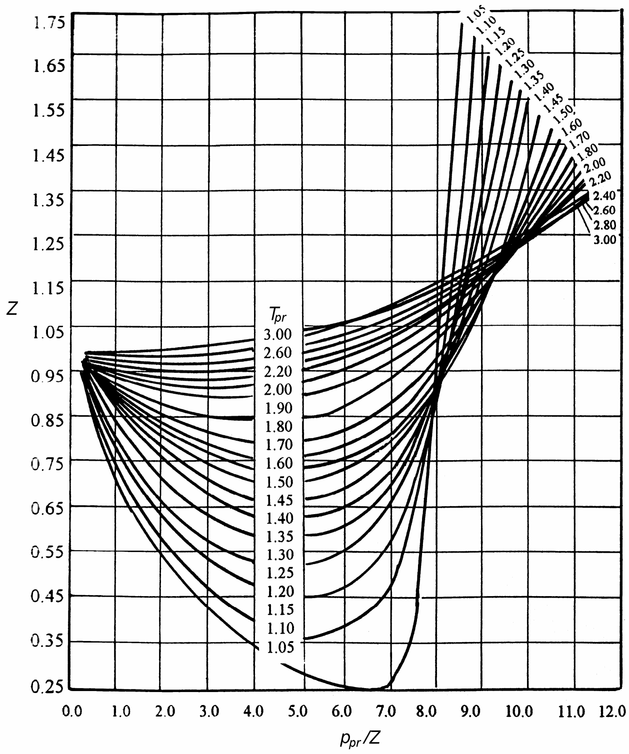

Figure 2. Gas deviation factor versus pseudo-reduced pressure and pseudo-reduced temperature

The zero-dimensional models, also known as volumic weighted average parameter models, are characterized by the average pressure defined as [1]

$$p_m = \frac{1}{V}\int_V p(x, y, z, t)\mathrm{d}V \ ,$$

so that between the average reservoir pressure p_m and the reservoir initial pressure p_i on one hand and the initial b_{gi} and current b_g gas volume factors on the other hand, the following relations

$$\frac{p_m}{Z_m} = \frac{b_{gi}}{b_g}\frac{p_i}{Z_i} \ , \tag{3}$$

$$\frac{p_m}{Z_m} = \frac{p_i}{Z_i}\left(1 - \frac{G_p}{G}\right), \tag{4}$$

exist, where the deviation factors $Z_m = Z(p_m)$ and $Z_i = Z(p_i)$ can be determined from Figure 2, according to the pseudo-reduced pressure and pseudo-reduced temperature defined by the equations

$$p_{pr} = p/p_{pc} \ , \tag{5}$$

$$T_{pr} = T/T_{pc} \ , \tag{6}$$

in which the pseudo-critical pressure p_{pc} and pseudo-critical temperature T_{pc} have the expressions

$$p_{pc} = \sum_{i=1}^{n} n_i \, p_{ci} \ , \tag{7}$$

$$T_{pc} = \sum_{i=1}^{n} n_i \, T_{ci} \ , \tag{8}$$

where n_i, p_{ci} and T_{ci} represent the molar fraction, the critical pressure and the critical temperature of the component i from the natural gas system considered, respectively [4, 6].

Case Study CS1

Let us consider a natural gas reservoir without water influx ($W_e = 0$) having the following data: daily gas production at the separator $G_{ps} = 267.8 \cdot 10^3\ \mathrm{m_N^3/day}$, condensate relative density $\rho_{ro} = 0.759$, daily ventilated gas production at the stock tank $G_{pr} = 803.9\ \mathrm{m_N^3/day}$, daily fresh water production $W_{pa} = 2.385\ \mathrm{m^3/day}$, reservoir initial pressure $p_i = 27.58$ MPa, reservoir temperature $T = 104.4$ °C, reservoir water salinity $S = 150{,}000$ ppm and the production time at constant flow rates $t = 1{,}000$ days. We intend to estimate the gas and water cumulative productions G_p and W_p necessary to finalize the zero-dimensional model corresponding to equation (1).

In order to approach this case study, we start from the assumption that the average daily gas production G_p of the reservoir is given by the equation

$$G_p = G_{ps} + G_{pr} + G_{pl} + G_{pa} \ , \tag{9}$$

where G_{pl} is the liquid production in the tank converted in an equivalent volume of gas, and G_{pa} – the production of water being in vapor state in the reservoir, for which the following formulas can be used

$$G_{pa} = G_{ps}\, c_a\, G_{pae} \ , \tag{10}$$

$$G_{pl} = \frac{n}{p_0} R_u\, T_0 \ , \tag{11}$$

$$n = \frac{\rho_o\, N_o}{M_o} \ . \tag{12}$$

In these relations, $R_u = 8.314$ J/(mole·K) is the universal gas constant, and M_o is the molar mass given by Cragoe's equation written as

$$M_o = \frac{44.29\,\rho_{ro}}{1.03 - \rho_{ro}} \ , \tag{13}$$

from which $M_o = 124.04$ g/mole results, for $\rho_{ro} = 0.759$. Then, the relation (12) gives the value $n = 145{,}958$ moles which, introduced into equation (11), leads to $G_{pl} = 3{,}270.87\ \mathrm{m_N^3}$.

The specific gas volume equivalent to a cubic meter of condensate has the expression

$$G_{pls} = \frac{G_{pl}}{N_p} = \frac{\rho_o\, R_u\, T_0}{M_o\, p_0} \ , \tag{14}$$

which can be used to calculate G_{pls} in standard conditions (15.6 °C, 101,325 Pa), as a function of ρ_o, as in Table 1.

Table 1. Condensate properties as functions of density

Condensate density ρ_o, kg/m^3	Condensate molar mass M_o, g/mol	Equivalent specific gas volume, G_{pls}	
		$\mathrm{m_N^3/m^3}$	$\mathrm{m_s^3/m^3}$
802	156	115	122
780	138	127	134
759	124	137	145
739	118	146	154
720	103	157	166

The water vapor content of initial gas in the reservoir is expressed as

$$G_{ae} = G_{aep}\, c_s \ , \tag{15}$$

where G_{aep} and the coefficient c_s are taken from Figure 1. For p_i = 27.58 MPa, T = 104.4 °C and the salinity S = 150,000 ppm, the values G_{aep} = 5,600 $\mathrm{kg/Mm_s^3}$ and c_s = 0.89 are obtained. Consequently, according to relation (10), we get G_{ae} = 4,984 $\mathrm{kg/Mm_s^3}$.

Taking into account that the daily hydrocarbon production has the expression

$$G_{ph} = G_{ps} + G_{pe} + G_{pr} \ , \tag{16}$$

the value G_{ph} = 287,352 $\mathrm{m_s^3/day}$ is obtained.

The water vapors volume equivalent to a cubic meter of liquid water is obtained from relation (14) particularized as

$$G_{pae} = 22.4 \frac{\rho_a}{M_a} \ , \tag{17}$$

G_{pae} = 1,244 $\mathrm{m_N^3/m^3}$ = 1,315 $\mathrm{m_s^3/m^3}$ resulting.

On the other hand, the volume of existent water vapors (in reservoir conditions) into the hydrocarbon daily production can be expressed by the formula

$$G_{pa} = \frac{G_{ae}\, G_{pae}\, G_{ph}}{10^6\, \rho_a} \ , \tag{18}$$

which gets the value G_{pa} = 1,883 $\mathrm{m_s^3/day}$.

Thus, the daily hydrocarbon production expressed in reservoir conditions is given by

$$\Delta G_p = G_{ph} + G_{pa} \ , \tag{19}$$

ΔG_p = 289,235 $\mathrm{m_s^3/day}$ = 273,656 $\mathrm{m_N^3/day}$ resulting.

The daily water production ΔW_p has the form

$$\Delta W_p = \frac{\left(W_{ps} - G_{ae}\right) G_{ph}}{\rho_a} \ , \tag{20}$$

where

$$W_{ps} = \frac{W_{pa}}{G_{ph}} \rho_a \ . \tag{21}$$

Using the data of this case study W_{ps} = 8,299.9 $\mathrm{kg/Mm_s^3}$ and ΔW_p = 0.953 m^3/day result.

Accepting that ΔG_p and ΔW_p are constant, the cumulative gas and water productions for t = 1,000 days involved by the material balance equation (1) have the expressions

$$G_p = \Delta G_p\, t \ , \tag{22}$$

$$W_p = \Delta W_p\, t \ , \tag{23}$$

from which we obtain the values G_p = 273.656·10^6 m^3, W_p = 953 m^3.

In fact, by decreasing the reservoir pressure, the parameters G_{aep} and G_{ae} increase (according to the plots in Figure 1) and, consequently, the daily productions ΔG_p and ΔW_p must be calculated according to time steps characterized by a small variation of the G_{aep} parameter as a function of the reservoir pressure. Thus, the cumulative productions G_p and W_p will be obtained by the sum of the $\Delta G_{pj}\, \Delta t_j$ and $\Delta W_{pj}\, \Delta t_j$ terms for all the time steps considered. While the salinity of the interstitial water increase by its vaporization, by calculating the salinity values S on the admitted time steps, the variation of the c_s coefficient can also be taken into account.

Case Study CS2

During the production of a dry gas reservoir, the production and pressure data presented in Table 2 were obtained. The reservoir has the temperature $T = 37.8$ °C and contains gas of $\rho_r = 0.68$ relative density. Based on the observation that the reservoir has impermeable boundaries, we intend to determine the following: a) initial reservoir pressure and geological resource; b) average reservoir pressure after producing, in the next 5 exploitation years, the $\Delta G_p = 566{,}000\ \mathrm{m_N^3}$ daily gas quantity.

Observing that the given reservoir is supposed to be deprived of water influx, the evolution of the average reservoir pressure will be described by equation (4). This supposition can be confirmed by the production and pressure data in Table 2, if the plot of p_m/Z_m versus G_p will consist of a straight line. In order to draw this plot it is necessary to previously determine the p_m/Z_m values.

Table 2. Production and pressure data for the case study CS2

Date	G_p, 10^6 m^3	p_m, MPa
1 07 1978	0	–
1 07 1979	51.225	23.8629
1 09 1980	110.464	23.2355
1 10 1981	165.653	22.1254
1 11 1982	267.622	20.8843

Table 3. p_m/Z_m versus G_p for the case study CS2

G_p, m^3	p_m, MPa	p_{pr}	Z_m	p_m/Z_m, MPa
51.225	23.8629	5.19	0.796	29.9755
110.464	23.2355	5.05	0.790	29.4120
165.653	22.1254	4.81	0.718	28.4388
267.622	20.8843	4.54	0.765	27.2997

The values of the pseudo-critical parameters corresponding to $\rho_r = 0.68$ are $p_{pc} = 4.60$ MPa and $T_{pc} = 214$ K. Consequently, according to the equations (5) and (6), the pseudo-reduced temperature is $T_{pr} = 1.45$, and the pseudo-reduced pressure has the values listed in column 3 of Table 3. For $T_{pr} = 1.45$ and the p_{pr} values in column 3, the Z_m values presented in column 4 were taken from Figure 2, to those the p_m/Z_m values centralized in column 5 of table 3 correspond. Based on these values, the plot of p_m/Z_m versus G_p in Figure 3 was drawn, obtaining a straight line which, extrapolated down to $G_p = 0$, leads to the value $p_i/Z_i = 30.737$ MPa.
Form Figure 2, for $T_{pr} = 1.45$ and $p_i/Z_i = 30.737$ MPa, the value $Z_i = 0.81$ can be taken, which leads, within point a), to the initial pressure $p_i = 30.737 \cdot 0.81$ MPa.

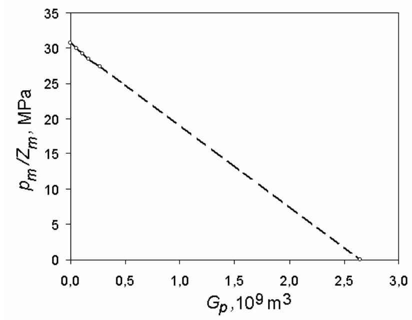

Figure 3. Plot of p_m/Z_m versus G_p for the case study CS2

On the other hand, the straight line in Figure 3 has the slope

$$i = \frac{-30.737 + 27.2997}{267.622} = -0.01284\ \mathrm{MPa}\big/\left(10^6\ \mathrm{m}^3\right)$$

and it is described by the equation

$$\frac{p_m}{Z_m} = 30.737 - 0.0128 G_p\ ,\ \mathrm{MPa}\ , \qquad (24)$$

from which the value $G = 2.394 \cdot 10^6$ m^3 of the gas resource results.

Within point b), the average pressure after 5 years of production, corresponding to the cumulative production

$$G_p = 267.622 + 0.566 \cdot 365 \cdot 5 = 1{,}350.572 \cdot 10^6\ \mathrm{m}^3$$

is obtained using equation (24) as follows

$$\frac{p_m}{Z_m} = 30.737 - 0.0128 \cdot 1{,}350.572 = 14.0376\ \mathrm{MPa}\ .$$

Then, from Figure 2, for p_m/Z_m = 3.052 and T_{pr} = 1.45, the value Z_m = 0.7526 is taken and, finally, for the average pressure after the next 5 production years the value p_m = 14.0376·0.7526 = 10.5647 MPa results.

Due to various reasons, getting the theoretical straight line of the p_m/Z_m versus G_p dependence in Figure 3 is often difficult. These reasons can be: the unexpected occurrence of a water drive process, owning inexact values of average reservoir pressure, as well as the presence of a pore volume variation in an unpredictable manner, as a result of abnormally high reservoir pressures.

Case Study CS3

The M layer [2, 3] constitutes a small gas reservoir which has the initial pressure p_i = 22.063 MPa and the temperature T = 104.4 °C. The pressure and production data, altogether with the volume factor values corresponding to this reservoir are listed in Table 4. We intend to establish the following: a) the gas resource values calculated at the end of each of the three production intervals, admitting that the reservoir has a volumetric behavior, which has to be checked; b) the plot of the p_m/Z_m ratio versus the cumulative production; c) the values of the cumulative volume of water penetrated into the reservoir at the end of each production year, knowing that the cumulative water production W_p is negligible, and the initial gas resource calculated from electric log and rock core data (by the volumetric method) has the value $G_i = 27.273 \cdot 10^6\ \mathrm{m_N^3}$.

Table 4. Pressure and production data for the case study CS3

Average pressure p_m, MPa	Cumulative gas production G_p, 10^6 m^3	Gasolume factor b_g, 10^{-3} m^3/m^3	p_m/Z_m, MPa
22.063	0	5.2622	25.186
20.167	2.1165	5.7004	23.250
17.409	5.9209	6.5311	20.293
14.501	12.1098	7.7360	17.132

In order to approach this study, the respective zero-dimensional model is used as follows.

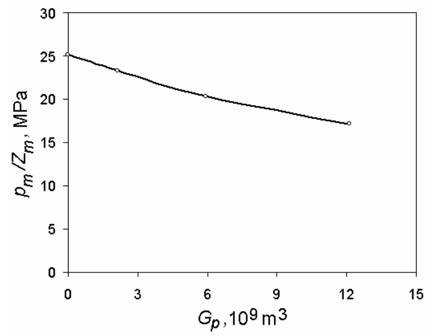

Figure 4. Plot of p_m/Z_m versus G_p for the case study CS3

Calling equation (2) and the data in Table 4, after the calculations, three different values result for the gas resource, namely: $G_1 = 27.5328 \cdot 10^6\ \mathrm{m_N^3}$, $G_2 = 30.4752 \cdot 10^6\ \mathrm{m_N^3}$ and $G_3 = 37.8694 \cdot 10^6\ \mathrm{m_N^3}$, showing that the reservoir is bounded by an active aquifer. For

$$Z_i = \frac{p_i\, T_i\, b_{gi}}{p_0\, T} = 0.876\ ,$$

the values of p_m/Z_m ratio calculated with the relation (4) and listed in the last column of Table 4 define the plot in Figure 4. The fact that this plot is a straight line confirms, once again, that the reservoir under analysis does not have impermeable boundaries.

Observing that the respective reservoir has water influx [1, 4. 6], from equation (1) reduced to the form

$$\frac{p_m}{Z_m} = \frac{p_i}{Z_i}\left(1 - \frac{G_p}{G}\right) \Big/ \left(1 - \frac{W_e}{G b_{gi}}\right), \qquad (25)$$

the cumulative water influx at the end of each of the three production intervals can be calculated, the following values: W_{e1} = 113.87 m^3, W_{e2} = 4.063.28 m^3 and W_{e3} = 26,213.46 m^3 resulting.

Conclusions

The simplicity in use of the zero-dimensional models, associated with the acceptable precision of the calculated results corresponding to the respective procedure, ensure a large applicability to these models in oil reservoir engineering as well as (and even more) in natural gas reservoir engineering.

To avoid committing significant errors when using zero-dimensional models for the production of gas reservoirs, special attention must be paid to the evaluations of cumulative gas production, average reservoir pressure, and cumulative water influx in the reservoir.

Due to water vapor and, sometimes, condensate content of reservoir gas, and to the extraction of these fluids by the wells together with the gas, it is imposed that the cumulative gas production also includes these fluid phases.

When estimating the average reservoir pressure, especially in cases when permeability is very low, it is necessary to use the well pressure buildup data.

The case studies approached in this paper and oriented to the interpretation of the performance of several gas reservoirs, led to the following considerations: a) the illustration of the procedure of taking into account the water and condensate volumes in the calculation of the gas production term from the material balance equation; b) the forecast of the reservoir pressure evolution, and c) the identification of the existence of an active aquifer by using production and pressure data within the zero-dimensional model corresponding to the respective reservoir, initially supposed to have impermeable boundaries.

References

1. Crețu, I. – *Hidraulica zăcămintelor de hidrocarburi*, vol. 1, Editura Tehnică, București,1987;
2. Crețu, I., Ionescu, E.M., Stoicescu, M. – *Hidraulica zăcămintelor de hidrocarburi. Aplicații numerice în exploatarea primară*, Editura Tehnică, Bucureşti, 1993;
3. Craft, B.C., Hawkins, M.F. – *Applied Petroleum Reservoir Engineering*, Constable and Company Ltd., 1959;
4. Crețu, I. – *Hidraulica generală şi subterană*, Editura Didactică şi Pedagogică, 1983;
5. Slider, H.C. – *Worldwide Practical Petroleum Reservoir Engineering Methods*, PennWell Publishing Company, 1983;
6. Crețu, I., Ionescu, E.M. – *Hidraulica subterană*, Editura Universității Petrol – Gaze Ploieşti, 2003.

Unele aspecte privind interpretarea performanței unui zăcământ de gaze din date de producție şi presiune

Rezumat

Mişcarea generată de sistemul sondelor extractive de gaze este reflectată în cadrul unui model zerodimensional prin variațiile în timp ale presiunii medii de zăcământ şi producțiilor cumulative de fluide. Deşi folosirea modelelor zerodimensionale pare simplă, pentru evitarea comiterii unor erori apreciabile, trebuie acordată o atenție specială evaluării producției cumulative de gaze, presiunii medii de zăcământ şi influxului cumulativ de apă. Lucrarea de față include trei studii de caz care ilustrează elocvent aspectele mai sus menționate.