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PRODUCTION DECLINE CURVE ANALYSIS FOR MATURE GAS RESERVOIRS SUBJECT TO REHABILITATION

1. INTRODUCTION

In Romania, the existence of natural gas has been reported long before the discovery and proper exploitation of the reservoir.

So there was highlighted, for the first time, a new energy bearing substance, and the event from the beginning of the past century, subsequently transformed, into a important economical segment with a infrastructure of appreciable dimensions.

A wrong perception is sustained in many companies, namely that, mature reservoirs are synonyms with nearly exhausted reservoirs, and that these assume just a few challenges against new discoveries. In reality, the majority of gas production in the world, comes from gas reservoir discovered from a long time ago, the pressing problems of these reservoirs are reffering to economical growth of the decline rate and improvement of the final recovery rate [1].

In principle, a number of possible options can be considered for maximization of mature gas reservoirs exploitation, although, as much as technical feasibility and every alternative costs must be carefully evaluated, before taking any decision. The expertise in different disciplines, as the knowledges possessed by the production and service companies must be well integrated, to be able to design successful interventions, in the context of high risk associated to every intervention in gas reservoirs where reserves are already depleted.

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Production decline under all its aspects, sometimes controllable, but more and more inconsistent with the growing demands of the natural gas market, has imposed a new approach on mature gas reservoirs which Romania owns, namely, their rehabilitation [2].

The present paper includes the production history analysis, decline curve engendering and analysis, and based on them, proposals regarding on production decline which will be applied to a agreed flow rate.

Throughout the exploitation of a gas reservoir generally there are distinquished several stages, such as:

- gradually increase of gas flow rates due to increasing gas wells introduced into production,
- maintaining of a quasi constant production,
- a accentuated decline of gas flow rates of the reservoir,
- a attenuated decline of gas flow rates of the reservoir.

The first three stages are quite short reported to the whole exploitation process of the reservoir.

The production decline appears sooner or later depending on the manifestation form of the reservoir energy [3].

To determine the production decline there has to be taken in consideration the following:

- production history is considered to be the starting point, represented in a software based on decline curve analysis;
- daily production tendency versus time is represented in semilogaritmical coordinates throughout the whole exploitation period of the reservoir;
- there are taken into consideration the specific exploitation stages of these reservoirs, the increasing production periods and also the decreasing production periods;
- because it is noted the existence of many periods characterized by different exploitation behaviours, to establish the decline there are selected, those periods to which it corresponds a quasi homogeneous behaviour;
- the decline used in the analysis is the exponential decline, in conditions in which the ongoing project contains production dynamics based on this type of decline;
- to highlight the production decline is used the historical regression line, whose slope indicates the value of the decline.

2. THEORETICAL ASPECTS

The decline curve analysis (DCA) is used for production forecasting of a gas well or a group of gas wells, but also for reserves estimation. The forecasting process is based on production history and is influenced by the wells mechanical problems. The forecast may be limited by flow rates or time.

The flow rate variation by time or by cumulative production is called decline curve, although from this the production decline cannot be read.

For a better understanding of the way in which the decline curves were engendered and analyzed, in the following the used terms will be defined:

- *Production history* – is represented by the whole recorded production per time unit on total deposit; in the present paper have been used the daily and monthly productions recorded throughout the exploitation.
- *Daily production* – represents an average value on every month in part, which results from the sum of daily delivered gas volumes throughout a month, reported to the number of days from the respective month.
- *Monthly production* – represents the monthly delivered gas volumes.
- *Production decline* – is represented as a variation in time of daily production and monthly production.
- *Decline curve* – is the graphical representation of the production decline.
- *Exponential decline* – represents the constant decrease in time of the daily and monthly production.
- *Exponential nominal decline* – is engendered in a decline curve analysis based software by the negative slope of the natural production logarithm versus time curve, and is defined as the report between the gas flow rate variation in time and gas flow rate itself, expressed by the following equation:

$$D = -\frac{\frac{dQ}{dt}}{Q} = -\frac{d}{dt}(\ln Q)$$

The nominal production decline rate equation shows the change in production rate per unit of time as a function of the production rate. With *constant percentage decline*, the change in production rate per unit of time is a constant function of the production rate, q. This means that the decline rate is constant. A negative sign is added to the right side of the equation so that it will have a positive value. If the variables of this relationship are separated, and integration takes place between the appropriate limits of flow rate and time, we obtain the rate-time relationship for the constant percentage decline curve.

$$q_t = q_i\, e^{-Dt}$$

This is the rate-time relationship for the constant percentage or exponential decline curve.

To obtain the rate-cumulative production relationship, we must integrate the flow rate, q_t, over the time period, t. q_i is the initial production rate and q_t is the production rate at some later time, perhaps at the time of abandonment if we are estimating future production. Note that is a fraction and not a percentage. This is the rate-cumulative production equation for constant percentage or exponential decline curves. As mentioned above, the decline rate is constant for constant percentage decline.

- *Exponential effective decline* – is engendered in DCA based software by production decrease between two moments, reported to the existent production at the beginning of the interval. If the time period is considered a month, then the decline value is the effective monthly decline. If the time period is considered a year, then the decline value is the effective annual decline. The effective exponential decline is a constant function on portions and hence it is used in full agreement with the actual production practices:

$$D_e = \frac{Q_{j-1} - Q_j}{Q_{j-1}}$$

  The annual exponential decline is obtained through mediation of all the monthly production values which involves the use of a single point per year.

- *Hyperbolic and harmonic decline* – for hyperbolic decline, the decline rate is proportional to a fractional power of q. This may be expressed as:

$$D = K q^n$$

  where n lies between zero and one ($0 < n < 1$).

- *Harmonic decline – f*or harmonic decline, the decline rate is proportional to q. This may be expressed as:

$$D = K q$$

We see, then, that the harmonic decline and constant percentage decline are special cases of the hyperbolic decline; that is, n is equal to 1 for the harmonic decline, and to 0 for constant percentage decline. On a more practical basis, we note that for both hyperbolic and harmonic decline curves, the decline rate will be highest initially and will decrease as the production rate decreases.

Each of the last two relationships may be integrated. We start with the hyperbolic decline relationship:

$$D = K\,q^n = \frac{\frac{d_q}{d_t}}{q}$$

Integrating this relationship between the appropriate limits of time and flow rate, we obtain the rate-time relationship:

$$q_t = q_i\,(1 + n\,D_i\,t)^{\frac{1}{n}}$$

We note that, in order to calculate a flow rate at any time, q_t, we must know the value of n and have calculated a value for D_i. We shall show how this is done shortly. With one more integration we may calculate the rate-cumulative production relationship. With this relationship and known values for q_i, q_t, n and D_i, it is an easy task to calculate the cumulative production, N_p. In order to develop equivalent relationships for harmonic decline, we begin again with a decline rate relationship, in this case:

$$D = K_q = \frac{\frac{d_q}{d_t}}{q}$$

To integrate, we separate variables and integrate between the appropriate limits of time and flow rate. This gives us the rate-time relationship:

$$q_t = q_i\,(1 + D_i\,t)$$

In this case, we see that the constant n no longer appears (it is equal to 1). We also see that we must know both the initial flow rate, q_i, and the decline rate at the initial flow rate, D_i, in order to calculate the flow rate, q_t. Once again, if we integrate the flow rate, q_t, with respect to time, we obtain the rate-cumulative production relationship. It becomes clear that our calculation procedures are sequential; that is, we must first determine the initial decline rate D_i, the initial production rate q_i, and, in the case of hyperbolic decline, a value for n. With these values, we use the rate-time relationship to calculate q_t and, then, knowing q_t, we use the rate-cumulative production relationship to calculate a value for N_p. With these relationships, then, we can calculate the flow rate and cumulative production at any given time.

In the year 1980, Fetkovich published his diagram, obtained through graphical representation at double logarithmical scale, based on the equation:

$$Q = \frac{Q_i}{\left[1 + n\,D_i\,t\right]^{\frac{1}{n}}}$$

of the values of Q/Q_i according to $D_i t$, for different values of the exponential n, including the values $n = 0$ (constant or exponential decline) and $n = 1$ (harmonical decline). A graphical representation for the flow-rate Q as a function of time t, shows the same slope with the type curve which has the same n. After identification the type curve, a common point of the two curves (the one obtained from production data and the type curve) allows the determination of D_i and Q_i parameters.

The following relationship can be used for cummulative production forecasting:

$$N_p = \int_0^i Q\,dt = \frac{Q_i^n}{(1-n)\,D_i}\left(Q^{1-n} - Q_i^{1-n}\right)$$

The Fetkovich type curves (Fig. 1) can be used for obtaining a approximate value for *n*, corresponding to particular set of data.

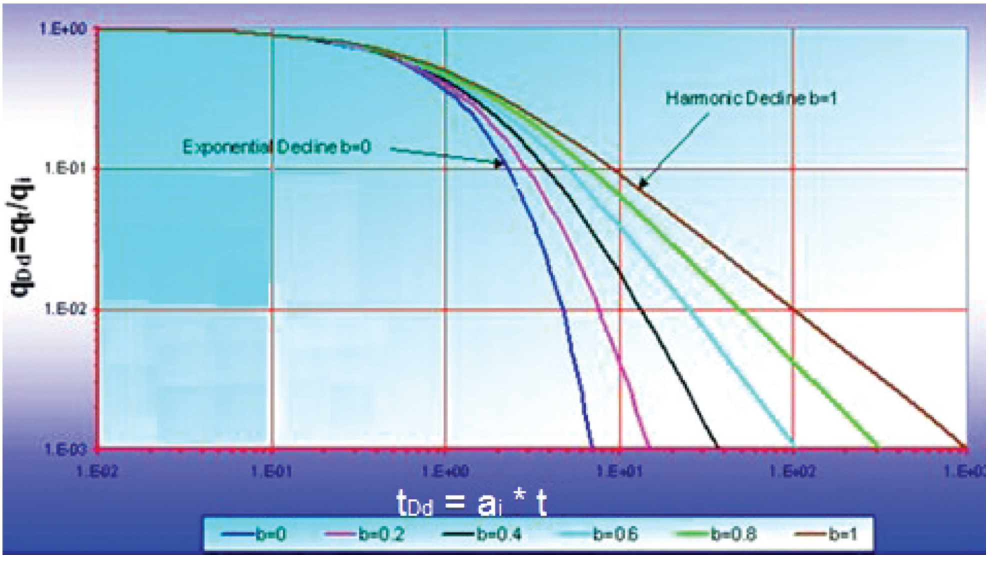

Fig. 1. Fetkovich type curves for decline equation

The production decline method application is realized in two stages:

1. in the first stage is determined the decline type, based on production history data;
2. in the second stage, by using the corresponding relations of the respective decline type, the reservoir exploitation behaviour forecast is realised, in the hypothesis that the exploitation conditions do not change.

3. DECLINE CURVE ANALYSIS – CASE STUDIES

This chapter includes production history analysis, engendering and decline curve analysis, and based on them, a proposal relating to reservoir decline in the new exploitation conditions. Based on this decline the base production dynamics will be build, the one who is totally recoverable by the company.

A. In the first example DCA engendering and analysis was made for a mature gas field, with exemplifying the operations that were performed in the wells. The production historical analysis per total field, Figure 2 (daily and monthly production versus time, in semi logarithmic coordinates – represented in DCA), indicates a inhomogeneous exploitation behaviour, which can be detected in several periods:

- 1975–1979: incresing production, in which the reservoir was developed.
- 1980–1983: decreasing production from a peak production, with a accentuated decline and a quasi-homogeneous behaviour.
- 1984–1992: decreasing production, with a accentuated decline and a inhomogeneous behaviour, defined by agressive seasonal fluctuations.
- 1993–2003: decreasing production, with a much attenuated decline as against the anterior periods and a quasi-homogeneous behaviour.
- 2004–2005: increasing production generated by workover jobs performed in the gas wells.
- 2005–2008: decreasing production, with a much attenuated decline comparable to the other periods and a quasi-homogeneous behaviour; to be mentioned that in this time interval no workover operations were performed in the wells, the production being maintained only by application of adequate extraction technologies.
- 2008–2015: increasing production followed by a alternation of increasing and decreasing productions with sensibly appropiate values, determined by performed operations in wells and mounting of compressor stations, and as well as by the variation of pressure in the collection system.
- 2016 (Jan.–Apr.): decreasing production with a very accentuated decline and quasi--homogeneous behaviour, determined by a decrease of gas wells production.
- 2016 (May–Oct.): increasing production, determined by mounting group compressors on 4 well groups.
- 2016 (Nov.)–2018: maintaining production, with a very attenuated decline as against the anterior periods and a quasi-homogeneous behaviour.

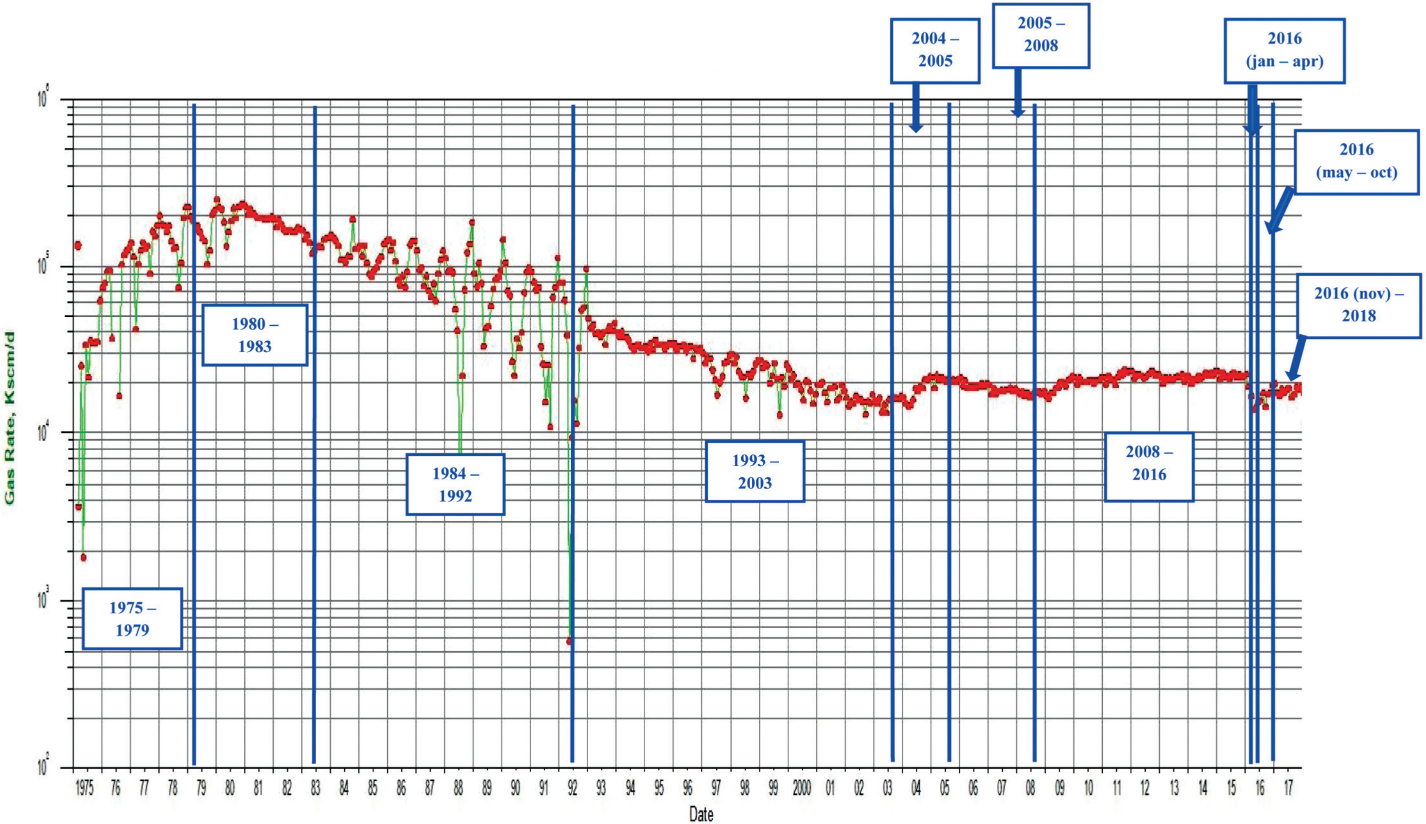

Fig. 2. Monthly production history per total deposit

From the anterior presented facts is highlighted a gradual exploitation, with different decline values, determined by the performed operations, the applied technologies and pressure variations in the collection system, combined with the deposits energetical level, corresponding to every exploitation moment.

At the beginning of the exploitation, when the reservoir energetical level is high, the value of flow-rate and differential pressures at the wells bottom (sole) are high as well, in conditions in which, according to fluid flow equation through porous-permeable medium, the two parameters are directly proportional. As the exploitation process is ongoing, in the first two stages of decreasing production (1980–1983 and 1984–1992) the reservoir energetical level decreases sharply and as a consequence the production decline is accentuated [4].

Starting from the premise that every hydrodynamical unit has an initial gas-water limit, once with the fall of the energetical level a water advance will take place due to capillary forces which manifest stronger to liquids than to gas. According to the state equation, once with the decrease of the initial gas saturated volumes will take place a attenuation of reservoir pressure drop, which will determine a reduction of production decline. This behaviour can be observed in the production history after the year 1993, when a changing of slope is seized in the sense of decline attenuation.

In the time interval (2004–2015) it can be observed a increase of flow rate and production due to improvement of well-layer flow conditions, by:

– operations performed in wells (withdrawals, additions, reperforations, deepenings, acid jobs);
– application of adequate extraction technologies (elimination of depressant elements, foaming agents introduction programs optimization, mounting compressors at well head or well groups)

In this stage of exploitation are highlighted periods characterized by the presence or absence of the production decline.

In the time interval (2016–2018) can be observed, mainly in the first interval of the year, a very accentuated decline of the reservoir (15%) due to dropping well production, and afterwards group compressor were installed which led to an increase of gas production and ulterior maintaining this production [4].

As the energetical level is dropping a semi-ficative attenuation of the decline per total deposit can be noted, which was generated in OFM, obtaining the following values:

– Effective annual exponential decline corresponding to daily production:
  • 1975–1979 – decline does not exist in this period of exploitation, it is the development stage, in which the production is increasing;

  - 1980–1983 – decline 13.9%;
  - 1984–1992 – decline 15.7%;
  - 1993–2003 – decline 9.3%;
  - 2004–2005 – no decline;
  - 2005–2008 – decline 7%;
  - 2008–2015 – no decline;
  - 2016 (Jan.–Apr.) – decline 15%;
  - 2016 (May–Oct.) – no decline;
  - 2016 (Nov.)–2018 – decline 0.5%.
- Effective annual exponential decline corresponding to monthly production:
  - 1975–1979 – decline does not exist in this period of exploitation, it is the development stage, in which the production is increasing;
  - 1980–1983 – decline 11.8%;
  - 1984–1992 – decline 15.9%;
  - 1993–2003 – decline 9.7%;
  - 2004–2005 – no decline;
  - 2005–2008 – decline 6.9%;
  - 2008–2015 – no decline;
  - 2016 (Jan.–Apr.) – decline 15%;
  - 2016 (May–Oct.) – no decline;
  - 2016 (Nov.)–2018 – decline 0.4%.

In this context, from production history, the periods closest in terms of time, with a quasi-homogeneous behaviour and exploitation conditions similar to the actual ones, are 1993–2003 and 2005–2008.

In this conditions, the regression line must not intercept extreme values, but to mediate the entire value range.

In the two periods (Figs 3–6), both the daily production and also the monthly production is in the form of an alternation of increasing and decreasing values, their variation being placed in an acceptable interval.

It has been noticed that since the beginning of 2004, although the exploitation of the reservoir has been intensified due to the accessing of new volumes of reserves, the tendency of the decline is to remain within a relatively limited range (6–7%). For example, the daily production corresponding to the time before the start of the well recompletion operations was 474 thousand cubic meters/day (March 2004), after which it increased to 715 thousand cubic meters/day (March 2005). The daily production in July 2008 was 532 thousand cubic meters/day, which implies a 7% decline.

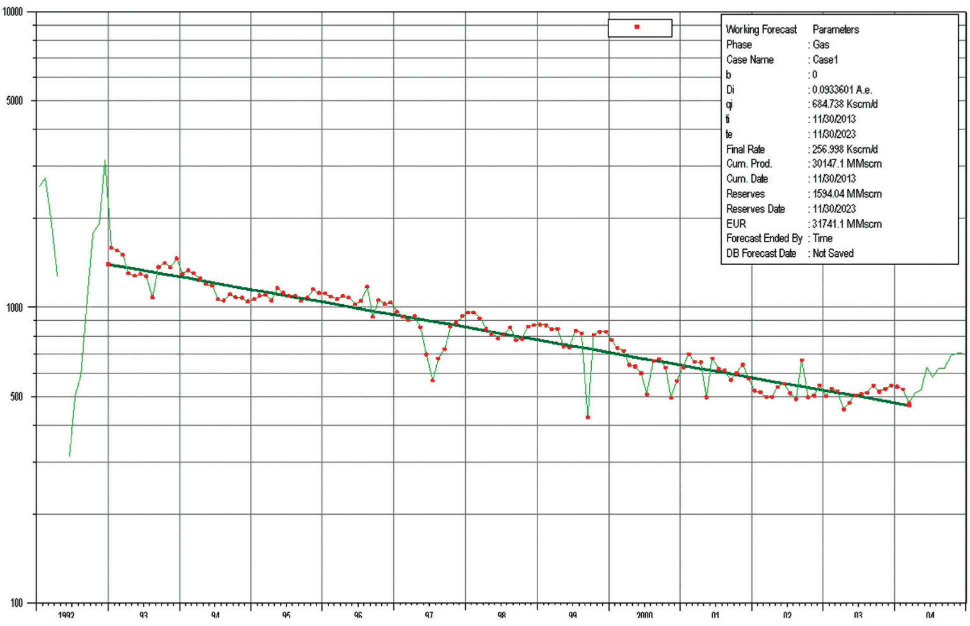

Fig. 3. Decline curve – daily production (1993–2003)

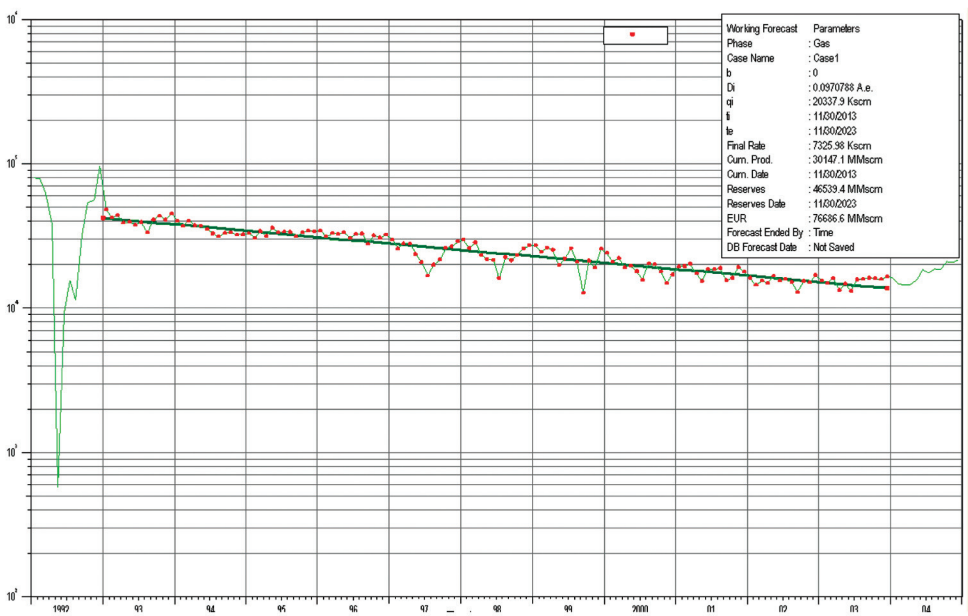

Fig. 4. Decline curve – monthly production (1993–2003)

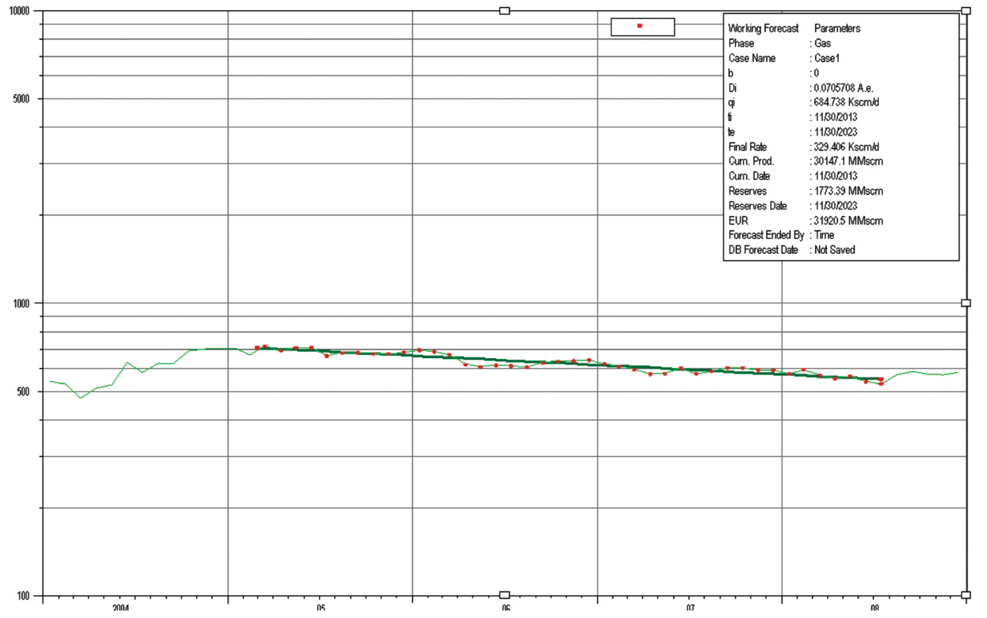

Fig. 5. Decline curve – daily production (2005–2008)

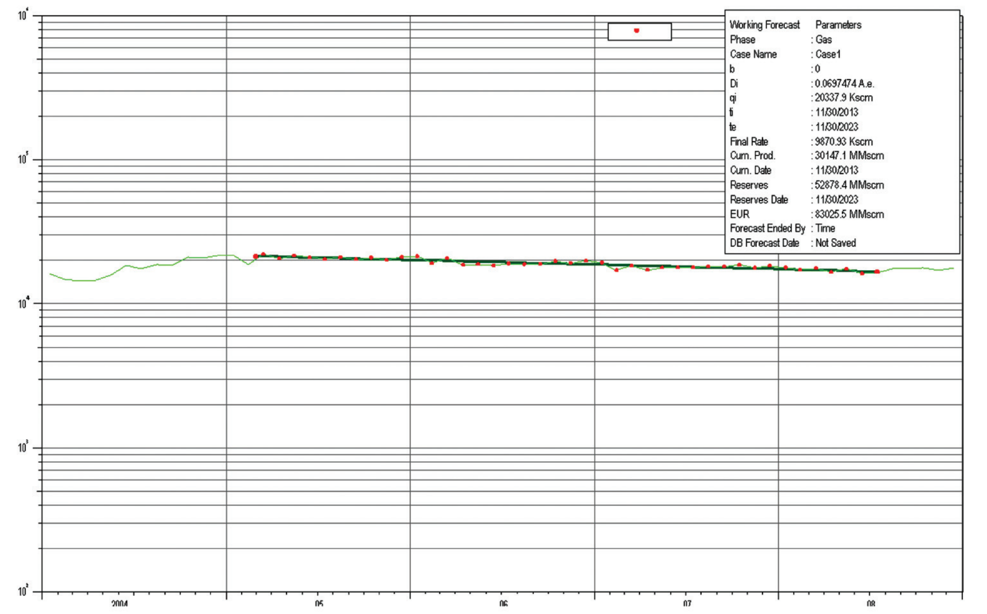

Fig. 6. Decline curve – monthly production (2005–2008)

The decline curve analysis was performed on the entire reservoir, not on each well or exploitation productive layer for the following reasons:

– After the period considered as a reference point for the decline, so after July 2008, a significant number of well interventions (13 recompletions and 9 reperforations) have been carried out, which radically changed the behaviour of the wells at the moment.
– The analysis of the production history and the establishment of a decline for the period (March 2005–July 2008), in the case for the wells on which interventions have been carried out after July 2008, are not relevant for the current exploitation manner.
– 11 wells have not experienced a decline in production during the period (March 2005–July 2008) and the other wells recorded production declines in a very large range (0.4–75.6%), which does not offer the possibility of establishing a realistic decline through a calculation algorithm.
– The production history of the entire reservoir, which implies much closer values, allows the trace of the decline curve with acceptable errors because it mediates a much narrower range of values (the average square deviation close to 1).

B. In the second example (Fig. 7), the decline curve analysis was used for supplementary reserves estimation obtained after interventions in six gas wells belonging to the reservoir. In all six wells supplementary sands were perforated, with positive gas indications in reservoir saturation investigations.

The methodology used in well intervention evaluation involved a series of activities, that were performed in order to evaluate well performance and improve forecasting capability of future performances:

– production history evolution review before and after intervention, mechanical and energetical decline determination of wells or production area with the aid of DCA software;
– reservoir saturation investigation interpretations review and production logging, using IP (Interactive Petrophysical) software;
– calculation of critical flow rate for all gas wells, based on borehole configuration, fluid properties (water density), well flow rate pressure system, using borehole pressure software;
– reserves estimate evaluation, before and after interventions, for every gas well, watching the exponential decline, up to the economical limit of 1000 m^3/day, using DCA software.

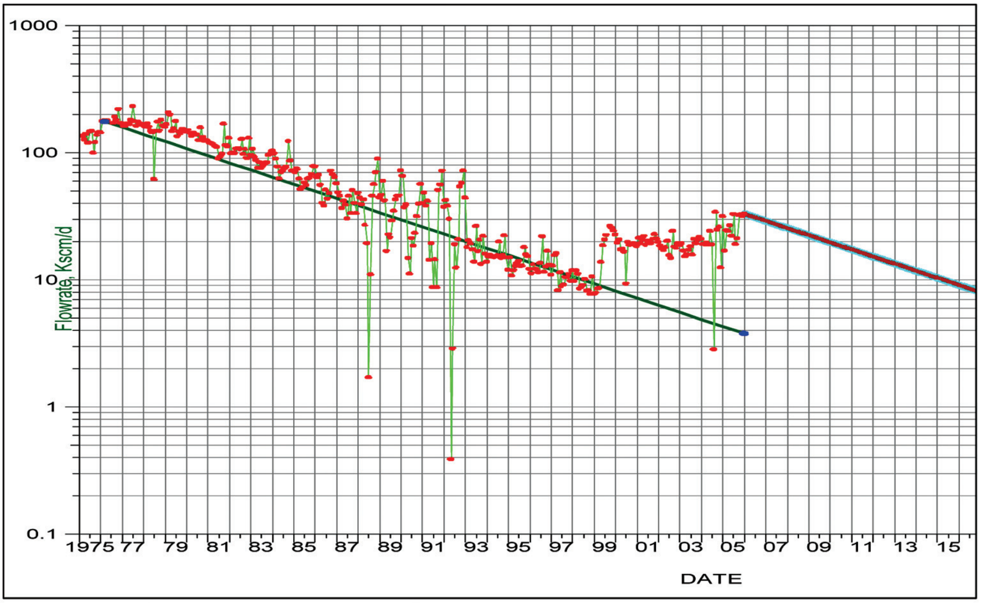

Fig. 7. Decline curve analysis

From decline curve analysis for the six wells to which we intervened, can be concluded the following:

- the intervention operations were successful, adding an approximately 150% to recoverable gas reserves existing for the six wells;
- the wells that are producing with higher flow rates than the critical flow rate after the interventions, does not show such a rapid decline like those that produce below the critical flow rate;
- merged productive packages adds up reserves, by extending the time before production drop below critical flow rate, and the well go into mechanical decline;
- reservoir saturation investigation logging represents a good investment for identification of unperforated areas with high gas potential;
- production log investigation which is adequate may be used for allocation of production on the packages.

Based on the results described above, using the presented methodology a DCA analysis was performed for every well from the deposit. Total reserves of the deposit were obtained from summing the individual reserves allocated for each gas well. It was considered that the proven reserves include those reserves which are in development and can therefore be estimated based on the decline curve. Because the probability of existence of these reserves are as 90% or higher, the decline curve technique was selected as being the best methodology, allowing reserves estimation with high degree of certainty [1].

4. CONCLUSIONS

Throughout the exploitation of a gas reservoir generally there are distinquished several stages, such as gradually increase of gas flow rates due to increasing gas wells introduced into production, maintaining of a quasi-constant production, a accentuated decline of gas flow rates of the reservoir and finally a attenuated decline of gas flow rates of the reservoir.

From the ones mentioned in the previous chapters it can be seen that the production decline specific to the reservoir is mitigation, as the exploitation process progresses.

Given the decline values that resulted from the analysis of the decline curves characteristic to all phases of the exploitation, for the upcoming period it is optimal to accept the specific decline of the last exploitation periods.

This behaviour indicates that under conditions of a further intensification of the exploitation, the decline will keep a value close to that of the last period.

Considering the rather advanced discovery of the reservoir, based on 3D seismic and complex investigations in the cased hole, the probability of finding a substantial additional volume of resources is very low. As a result, the exploitation is assumed to be ongoing according to current estimates, without major modifications of the production decline.

Golden rule of decline curve analysis as a basic assumption in this procedure is that whatever controlled the trend of a curve in the past will continue to govern its trend in the future in a uniform manner [5].

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