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REHABILITATION OF DEPLETED NATURAL GAS DEPOSITS

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Abstract: *The exploitation of natural gas deposits is subject to a great dilemma; as the gas reserve is exhausted, the demand for this fuel (in the area where the exploitation is located) increases. That is precisely why operations are needed to increase the final recovery factor and allocate new financial resources when the deposits no longer provide the quantities of gas required for demand or the pressure in the deposit is low enough to make exploitation profitable. In this article, the management principles of rehabilitating depleted gas deposits are stated, emphasizing the establishment of the minimum techniques for their control and exploration.*
Keywords: *natural gas, rehabilitation, management of depleted fields.*

1. Introduction

There are two contradictory trends in the exploitation of gas fields.

With the advancement of the field's exploitation (advancement in the lifetime of the gas structure), the flow of gas decreases (there is a decrease in the quantities of gas delivered), with the increase of the quantities of gas requested (in the area where the field is located), both for consumers industrial and domestic (increasing the level of comfort).

Supplementing the required amount of gas and implicitly increasing the recovery factor of the deposit is achieved by [1];

- identification of new gas accumulations within the exploitation objectives;
- identification of new gas accumulations between exploitation objectives;
- the identification of new gas accumulations outside the exploitation objectives,
- analysis of the continuity of gas accumulations between the approved exploitation perimeters and outside the exploitation perimeters.

These methods are based on the results of new geophysical investigations, existing data reanalysis, and deposit model reconstruction. The recovery factor (at a given time) is given by the ratio between the amount of gas extracted up to the time of analysis (ΔG_a) and the initial gas resource (ΔG_i).

$$FR\ (\%) = \frac{\Delta G_a}{\Delta G_i} \tag{1}$$

The final recovery factor is determined at field closure and would ideally be 100%.

But in practice, this desired is difficult to achieve for the following reasons [2]:

a. the existence of quantities of gases trapped in the pores that do not communicate with the flow channels,

b. the progressive increase in pore water saturation (at deposits containing an active aquifer) and, therefore the decrease in gas flow capacity through flooded pores,

c. lowering the energy of the deposit by reducing its pressure,

d. corrosion of gas installations and the possibility of technical accidents occurring during current maintenance operations,

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e. the advancement of the well condensate in the pores of the rocks and the extraction zone (by decreasing the gas pressure),

f. the appearance of water in the extraction area (of the biphasic flow) will decrease the well's cutting capacity.

In production practice, gas fields without an active aquifer have a final recovery factor of 85-90%. In comparison, mixed ones (with an active aquifer and condensate) have a final recovery factor (on the exploited structures) of a maximum of 80% [3].

The use of natural gas as a transitional fuel, and significantly the increase in the quantities of gases required for chemical processing and their cracking to obtain hydrogen (as a fuel), makes the depleted deposits be used as suppliers of natural gas (by increasing the factor final recovery) and especially as future carbon dioxide storage depots.

In most exploited natural gas fields, increasing the life of the wells, especially by keeping the extraction area clean, can increase the final recovery factor [4].

The flow regime of the gas wells (at the beginning of exploitation) is stable, even if liquids (condensate/water) accumulate at the bottom of the well.

With the increase of the extraction period and, therefore, the penetration of liquids into the bottom of the well, the gas flow reduces (arriving at an unstable flow), and the removal of water is partially achieved.

As the amount of water increases and the reservoir decreases (the well's hydrostatic column being equal to or greater than the reservoir pressure) the well no longer flows.

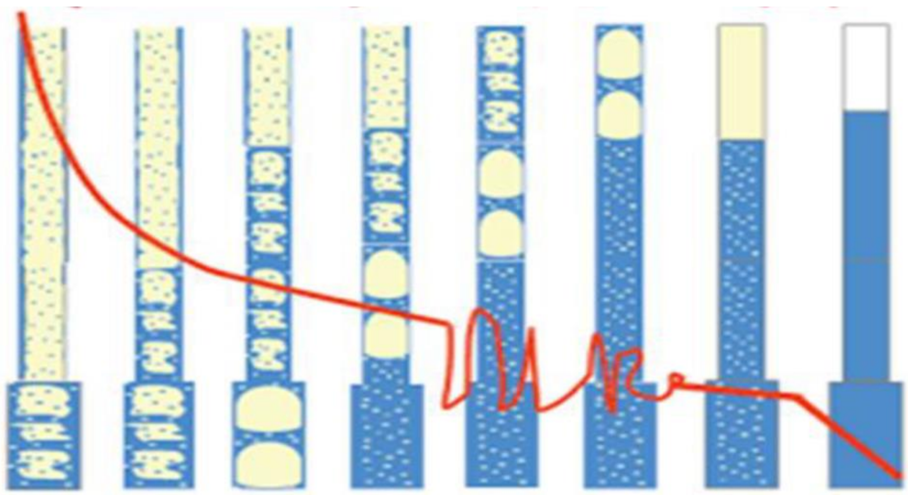

Fig.1. The variation of reservoir pressure depending on the presence of liquids in gas wells

To achieve the highest possible recovery, it is necessary to maintain the flow of the well in the stable field through specific operations and interventions with different degrees of complexity.

2. Management of the growth of the final recovery factor

2.1 Identification of new horizontal gas accumulations within the exploitation objectives

This identification requires an in-depth knowledge of the deposit's geometry and petrophysical properties, namely the deposit's anisotropy of porosity, permeability, and degree of connectivity.

These variables are primarily related to changes in sedimentary facies (a depositional environment, also known as a sedimentary environment, represents a physiographic setting where sediments are deposited.

This environment can be a river, a lake, a delta, a lagoon, or even the vast ocean. Each depositional environment leaves distinctive signatures on the sediments specific to the processes active during sedimentation. These signatures include fossil associations, sedimentary structures, and lithological properties known as sedimentary facies).

Their knowledge is closely related to the existence of an updated 3D deposit model that is as close as possible to the reality in the field (Figure 2).

The left side of the image represents the initial state of the resources, and the right side is the current resources.

An almost undrained area in the southern part of the deposit is observed, for which it is proposed to drill an exploitation well.

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This situation occurs mainly in deposits with moderate horizontal permeability, where the entire functional surface cannot be drained even for a long time.

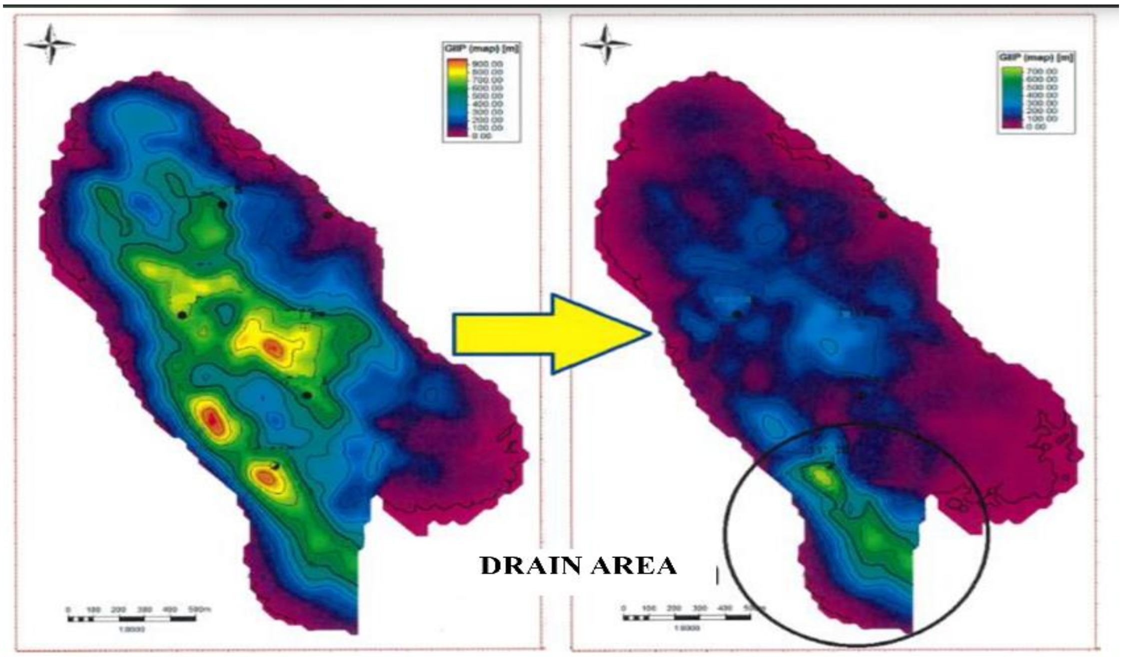

Fig.2. Identification of new horizontal gas accumulations within the exploitation objectives

2.2. Identification of new vertical gas accumulations within the exploitation objectives

Identifying gas accumulations that can be exploited within an exploitation objective is the first step in the strategy of rehabilitating a deposit.

Multiple perforations can increase the final recovery factor for reservoir collectors, applying perforations over unopened areas within the objective.

The chance of success is primarily related to the difference in horizontal/vertical permeability, in the sense that the existence of undrained areas has more chances in the case of lower vertical permeability.

Figure 3 shows such a case. Initially, there were 9 (nine) open intervals (marked between the blue arrow) with an advanced degree of depletion.

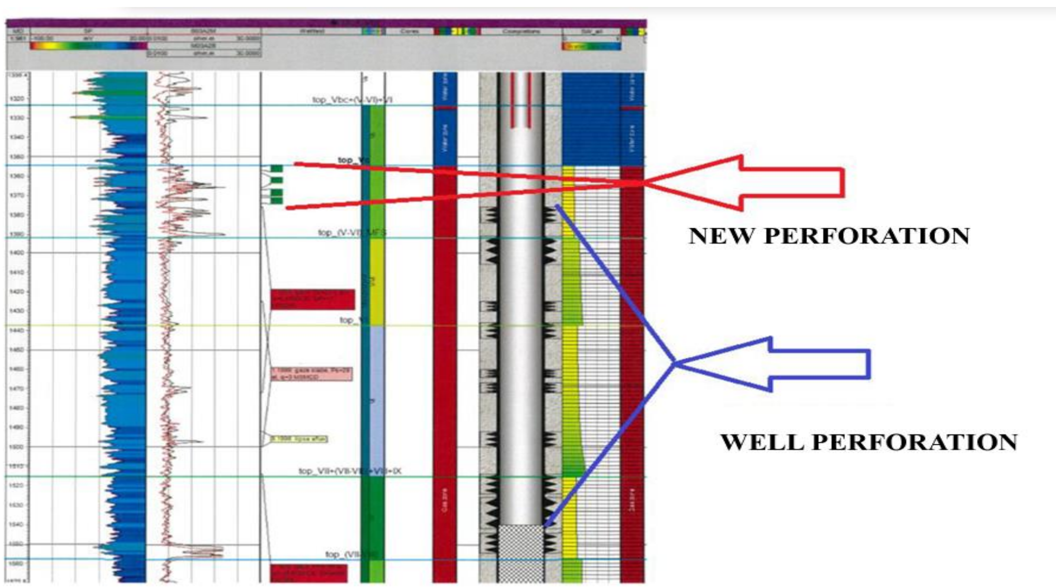

Fig.3. New perforations to gas well proposed

By adding the objective cap (red arrow), the flow rate increases, implicitly increasing the reservoir's FFR%.

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There is also the rarer situation when the well's geometry, by the existence of a sufficient distance between the base of the perforations and the mirror of the isolation plug in the column, allows addition over the gas-saturated zone below the existing perforations.

This case must be carefully analysed because, with the descent of the perforations, the gas/water contact is almost reached in the transition zone, where the production of a significant amount of water is also likely, which would negatively influence the performance of the gas well.

Another case, primarily related to very low vertical permeability, is when "skipped" areas, not initially opened, were identified between the existing perforations.

Figure 4 shows such a situation. Old perforations are marked with black arrows, with red ones added later.

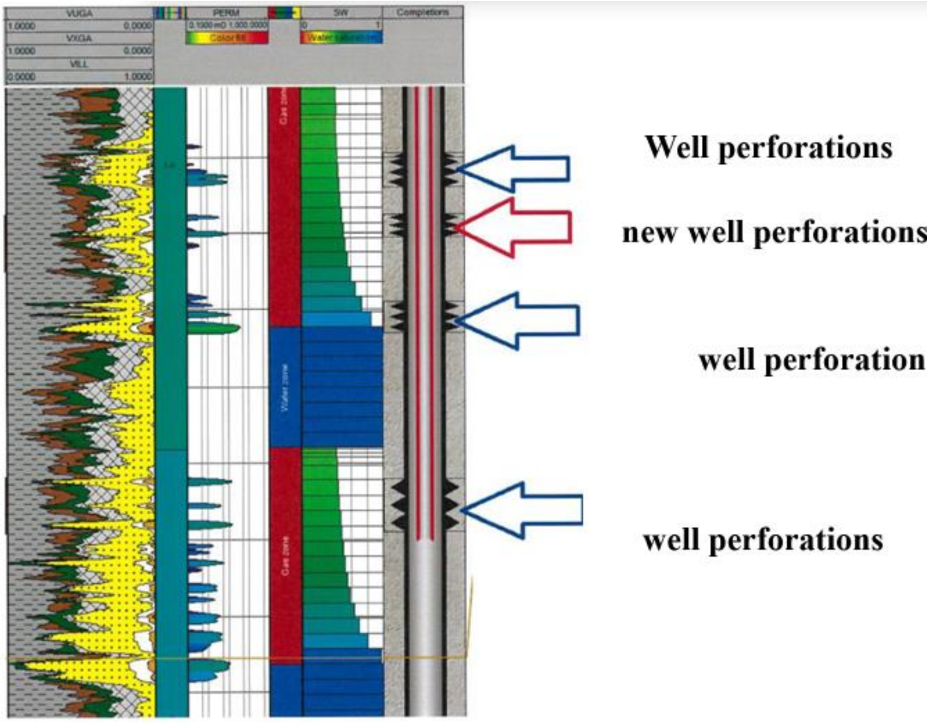

Fig.4. Another well perforations

2.3. The identification of new gas accumulations outside the exploitation objectives through the possibility of their continuity outside the exploitation perimeters

There are situations where, due to the initial level of knowledge, the size of the deposit was underestimated. Based on the initial model resulting from the initial studies, the exploitation perimeter was outlined and materialized through a concession agreement.

Later, various works—seismic investigations, balance analyses, dug exploratory wells—identified a continuity of the deposit outside the established perimeter.

Depending on the concessionaire situation, there are the following cases:

• the area outside the production perimeter is free, not granted by another company. In this case, with the agreement of the authorities, the exploitation perimeter can be extended over the new part of the deposit with supporting documentation;

• the surface belongs to an exploration area of the same company that owns the exploitation perimeter. In this case, the solution is identical to the previous situation; the extension of the perimeter is also done with the consent of the authorities

• When the deposit's surface extends over an exploration or exploitation concession belonging to another company, a joint agreement between the two companies will be necessary, with the possible fair sharing of future production, also only with the consent of the authorities.

Figure 5 shows a deposit extension identified after 3D remodelling.

The red surface represents the gas zone, and the blue is the adjacent water zone.

The purple line is the current mining concession boundary.

To capitalize on the gas accumulation outside the perimeter, an exploitation well will need to be placed on the current concession line, but beforehand, the competent authority will be requested to extend the concession over the new part of the deposit.

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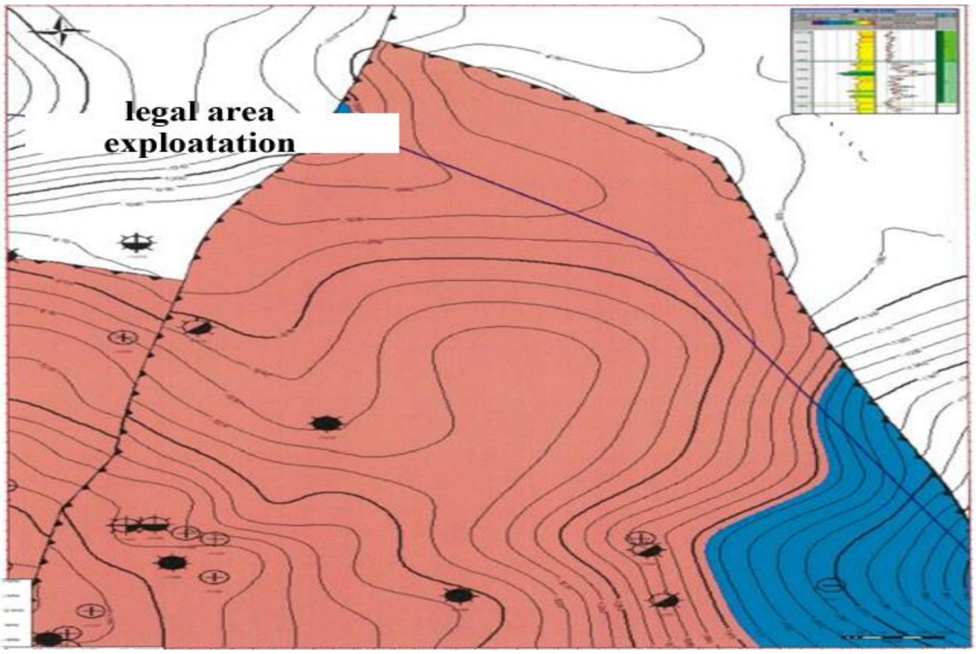

Fig.5. New gas accumulations outside the exploitation objectives

3. Work in wells to increase the recovery factor

For optimal gas well operation, the hole must be kept as clean as possible. Liquid and solid impurities that accumulate in the bottom of the well and are not removed can significantly reduce the well's life, thereby reducing the value of the final recovery factor.

3.1. Reducing downhole flow blockage by removing liquid impurities

The most common operation to remove water accumulated in the bottom of the well is levelling using liquid nitrogen.

Nitrogen, an inert gas and a component in ¾ of air does not require special treatment after removal from the borehole.

Liquid nitrogen is used to achieve the pressure necessary to blow the amount of liquids, and it is transported in special tanks at -196 gr C.

The converter unit transforms them into gas, which results in the pressure required for the levelling operation.

The amount of liquid nitrogen removed is calculated based on the amount of liquids to be removed, the depth and volume of the borehole, and the static pressure of the open objective to prevent nitrogen from entering the reservoir area.

The volume conversion factor is taken into account in the calculations: 1 m3 of liquid nitrogen turns into 750 m3 of gaseous nitrogen.

The obtained nitrogen gas is pumped through the extraction pipe, and the mixture is recovered through the valves in the column. The idea is to create an additional pressure as low as possible over the productive layer, with the volume of liquids in the annular space having a lower height than in the tubing.

After obtaining the nitrogen circuit, a break is needed to settle the liquids raised on the pipe wall. After that, the operation is resumed to clean the hole through reverse circulation and column—-tubing.

This operation has a high efficiency/cost ratio, is quick in time, and ensures long production even in some depleted wells with continuous fluid flow to the wellbore.

3.2. Reducing downhole flow blockage by removing solid impurities

In the mining process, solid particles, in addition to liquids, also accumulate at the bottom of the borehole.

A significant amount of solids also blocks part of the perforations, reducing the adequate flow thickness. For their removal, the operation with flexible tubing is used.

Using a special blowout preventer mounted over the blowout head, the flexible tubing liner is inserted to the desired depth above the solid deposit, after which water is pumped under pressure through the flexible tubing to remove the solid deposit.

The end of the flexible tubing can be equipped with a washing head, which directs water through holes to wash the deposits more efficiently.

The methods can also be combined.

In the case of a depleted reservoir, continuous water flushing would create over-pressurization, which would reduce flow performance.

In such cases, a water plug is inserted, which, in the flexible tubing, creates a hydrostatic pressure lower than or at most equal to that of the deposit's static pressure. After that, nitrogen is injected to remove it from the borehole.

The operation is repeated until the hole is cleaned. The injected water mixed with the solids is removed either in the annular space between flexible tubing or between flexible tubing columns.

Another method uses the extraction gasket for direct flushing, provided the extraction pipe is below the deposit in the annulus.

In this case, pump a plug of water followed by a nitrogen jet, repeating the operation until it is cleaned.

It is most often used in wells, where the tubing is inserted at the base of the perforations. During mining, the solids coming out of the perforations create a sleeve in the annular space.

The advantage of this method is the reduced operating cost of the flexible tubing unit.

3.3. Reduction of the skin in the invasion zone around the borehole by re-perforations

During prolonged mining, the flow channels behind the perforations can become clogged, reducing the formation's flow capacity.

In this case, re-perforating the area is a remedial solution.

Over time, these flow channels around the well may become altered due to salt precipitation from the reservoir waters or clogged with fine salty material entrained from the bed.

Modern drilling systems have far superior performance to those used in the past for most wells in depleted deposits.

If in the past they used perforators with 9-13 bullets per meter, nowadays they have 20.

The phase difference between them in the past was 1800, and the modern ones have 600. The penetration power is doubled, reaching 1 m from the axis of the probe.

In addition, modern prevention systems allow perforation under pressure; bullet segments can be fired in both liquid and gaseous environments.

All these advantages suggest re-drilling the wells if indications show the existence of sufficient resources.

3.4. Isolation of aggressive aquifers occurring during mining using mechanical plugs and mechanical / hydraulic packers

When a deposit is exhausted or when a more significant amount of water appears at the bottom, it is necessary to isolate the area.

In the past, the common practice was to seal with a cement plug pumped through the extraction pipes.

With the depletion of deposits, this operation became much less precise.

The operation involves filling the borehole with liquid, which creates a significant overpressure over the depleted layer. Often, the amount of cement entering the perforations requires repeating the operation, even several times.

This impediment is eliminated by fixing mechanical isolation plugs, which are launched with the geophysical cable at the desired depth and fixed by detonation in the column.

Another situation arises when it is necessary to isolate different open objectives in the wellbore for the purpose of dual, simultaneous production.

Another case is when hydraulic fracturing operations protect the mining column. A similar situation is in the case of water injection wells, where protecting the column is essential.

Equipping with packers is also used in column breaks next to higher aquifers to preserve the productive layer from the inflow of water. Modern packers are inserted using extraction pipes.

Multiple packer systems can also be introduced in the column.

Packers can also be recoverable; their extraction is also done with the help of extraction pipes. Their arming can be done either mechanically or hydraulically.

Most modern packers are inflatable, allowing them to be converted to column restraints.

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3.5. Withdrawals and returns to higher/lower objectives, after exhausting the current ones, diagnosed by the material balance method

Applying the material balance is different from an actual intervention in the borehole.

This chapter briefly presents the method since it is the basis of all economic calculations when analyzing the feasibility of proposed operations.

Considering that any operation involves an expense, sometimes quite important, it is necessary to know the volume of gas that can be used after the operation.

This method requires a series of reservoir measurements recorded during the well's production period from the same target, together with the cumulative gas values extracted up to that time.

Considering the elastic expansion model of gases, with no water push, the Pz/Z (pressure field) vs. GP (production rate) plot is constructed, and ideally, the points line up on a straight line.

Its intersection with P_Z/Z at the deposit abandonment pressure indicates the useful geological resource for the respective objective (Figure 5).

The remaining gas and the current final recovery factor can also be deduced from the graph.

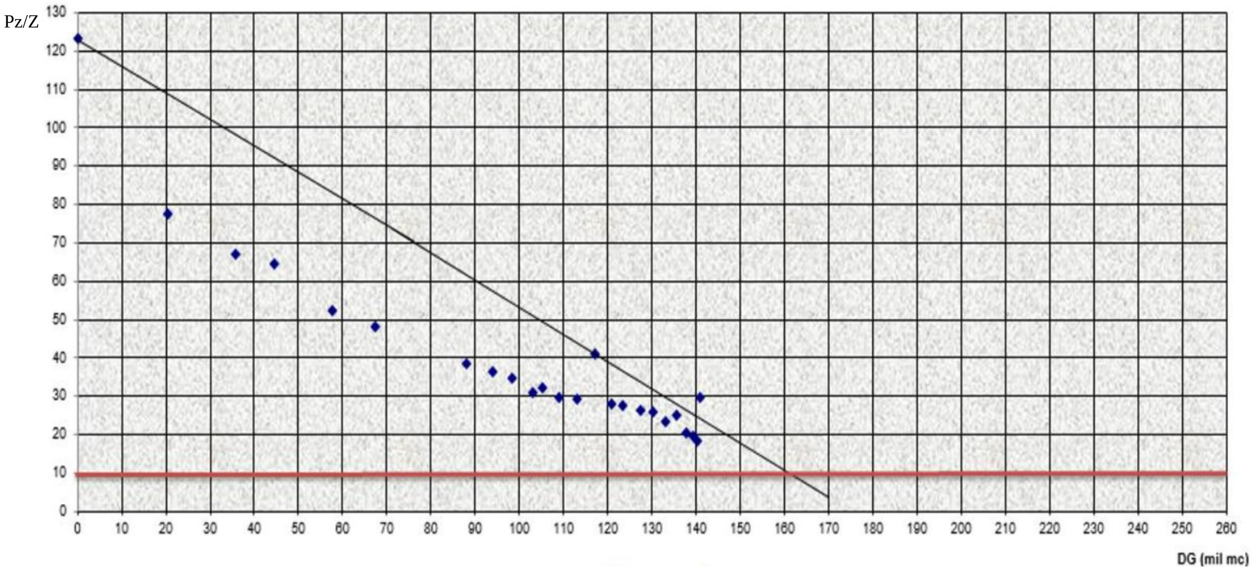

Fig 5. Material balance curve for well resource identification (P_z/Z function to production rate)

3.6. Pressure handling of the extraction pipe assembly with the snubbing installation

Many healthy intervention operations in the past required injecting fluids into the wellbore to balance the static pressure, as much as 1.2-1.5 times, to work safely.

In depleted deposits, this measure compromised the operation in many cases, with the over-pressurization creating a blockage at the layer level that could not later be improved.

Most operations - drilling with increased diameters, setting mechanical plugs, inserting packers, production coring operations, etc. – involved handling the extraction pipes, automatically killing the probe.

The use of the automatic snubbing facility eliminated these impediments for depleted fields.

The installation consists of a preventer mounted over a safety valve, which is, in turn, mounted over the tubing of the eruption head.

The tubing is depressurized after a plug at the bottom is fixed.

The preventer's sealing allows the extraction pipes to be moved up or down. The probe remains in production on the column throughout the operation, so there is practically no non-productive time.

At the last stage of operation, a ceramic plug is attached to the end of the extraction pipes, which is later broken with a lance, or a nipple plug is connected and retrieved with wire equipment.

Figure 6 shows the scheme of a snubbing installation working at great depth. In the usual ones from the Transylvania basin, the aforementioned safety valve takes over the role of the preventers in the picture.

Snubbing units are mainly used for drilling operations and adding productive strata. Drilling is thus carried out without introducing liquids into the well, and the strata are produced in the collectors immediately after their opening.

The eruption head must be slightly modified to the snubbing type for safe snubbing operation, with side bolts to block the extraction pipe assembly

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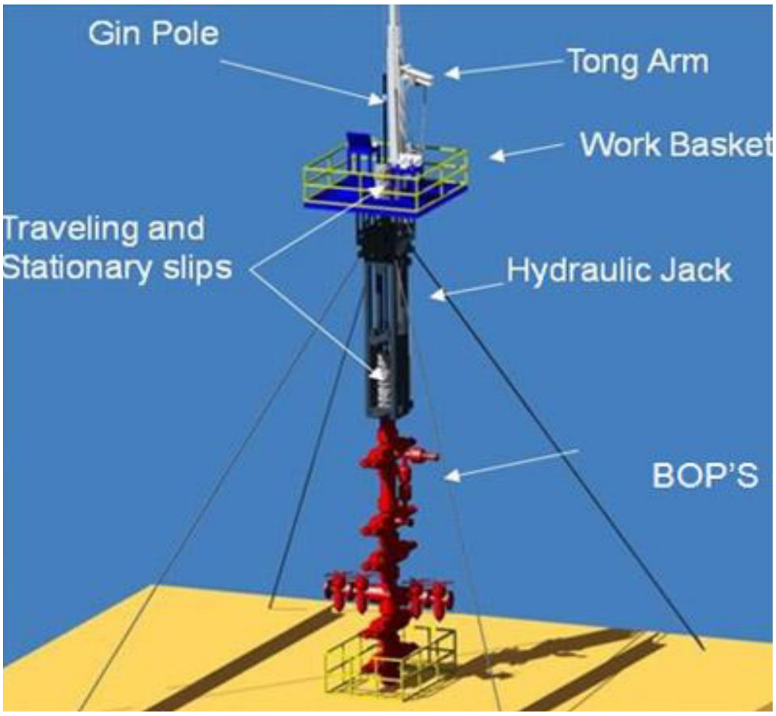

Fig. 6. Schematic of a snubbing unit

4. Works performed at the deposit level

To understand the phenomenon of increasing the final recovery factor for the entire deposit, not only at the level of individual wells presented so far, it is necessary to study the stationary flow equation in the permeable porous medium, which has been characteristic for most of the deposit's life.

This simplified equation has the following form:

$$P_z^2 - P_c^2 = A \cdot Q + B \cdot Q^2 \quad (2)$$

Where P_z is the current reservoir pressure, P_c is the pressure at the level of the perforations, Q is the well's flow rate and A and B flow coefficients.

In depleted deposits, the flow is no longer turbulent, so the quadratic term with coefficient B can be neglected.

Expressing the gas flow from the equation, we have:

$$Q = \frac{P_Z^2 - P_C^2}{A} \quad (3)$$

To increase the gas flow, among the three variables, the reservoir pressure is given; we cannot improve it.

Coefficient A is expressed by:

$$A = \frac{\mu ZT}{kh}\left(ln\frac{R}{r} - \frac{3}{4} + S\right) \quad (4)$$

Gas and reservoir rock parameters are constant.

The only values that can be changed in this equation are the effective h-thickness and the S-skin of the probe—assuming that by re-perforating and adding h, it has been increased and S decreased to the limit of possibility.

Thus, we can only obtain an increase in flow rate by lowering the P_c value.

These ways of reducing collection pressure are discussed next.

There is a strict relationship between the collection pressure in the pipes (P_{pipe}) and the pressure in the bottom of the well:

$$P_{pipe} = P_c - P_{loss} \quad (5)$$

where P_{loss} is the sum of the pressure loss through the extraction pipes and the collector ramp, relatively constant at low flow rates in depleted deposits.

Thus, the value of P_c can be reduced by lowering the collection pressure P_{pipe}.

Different types of compressors play a decisive role in this process.

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4.1. Reduction of collection pressure at the level of the eruption head

In recent years, the idea of increasing the recovery factor has led to lowering the collection pressure without installing large, expensive compression stations with impressive infrastructure.

The technology used is mounting the compressors directly to the eruption head.

It is common practice to mount several GasJack compressors in parallel when a large volume of gas is required.

Direct-to-head compression reduces tubing head gas pressure below the levels possible with centralized compression systems, which are limited by pressure drops between the head and centralized compression stations.

By reducing the pressure at the blowout head, gas production increases due to decreased flow back pressure.

As a result of the decrease in back pressure, the flow rate increases and implicitly helps the well to lift the liquids, which leads to further growth in production.

4.2. Reduction of the collection pressure at the deposit level

Using large compression stations for large fields with an advanced degree of depletion is a practice that has been around for several decades.

The suction pressure, which at the beginning was 8-10 bars, by modifying the compressor units, followed the needs by lowering the value, reaching 2-3 bars.

The results are evident by maintaining increased production over the long term.

However, as they are very large investments, their realization requires a severe feasibility study. As a complex problem, a deep nodal analysis of the reservoirs serving the station, the existing gas wells, and the gas collection system is needed.

The importance of reservoir pressure is crucial. A quick calculation regarding the flow rate increase at different values of the reservoir pressure is shown graphically in Figure 7.

Applying the stationary flow formula and using a hypothetical suction pressure of 2 bar and a constant pressure of 6 bar at the level of the perforations at the eruption head, the flow increase in percentages compared to the situation where the compressors would not operate was achieved.

The result demonstrates the growth in compressor efficiency at low reservoir pressure values.

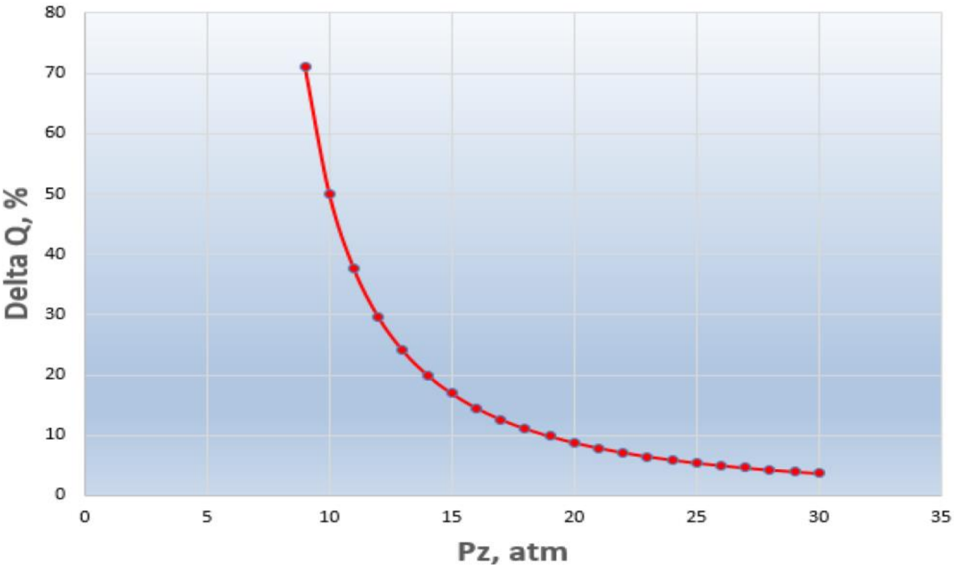

Fig. 7. The relationship between the flow rate increases after different values of the reservoir pressure

4.3. Reduction of pressure losses by reconfiguring well adductions

The pressure losses encountered in the gas collection system can be crucial in fields that are becoming increasingly depleted.

If in the case of high flow rates in the early period of production, the losses were mainly due to the friction of the gas having high transport velocity through the pipelines, the reduced flow rates with depletion reduced their importance.

Instead, with the increase in liquid impurities, pressure losses occurred due to liquid plugs accumulated in gas supply pipes.

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The separators are clogged with solid particles resulting from long-term exploitation, and these plugs of water driven by the wells manage to pass the separators and reach the collector ramps. T

he gas must pass these plugs in the pipes.

Gas production in depleted deposits can become very sensitive to pressure losses due to values between 2 and 4 bars.

Their remediation can be achieved through the following solutions:

• The installation of intermediate separators at the critical points of the adduction: valley crossings, hill climbs, sudden changes in direction, and diameter variations, which favour the accumulation of water plugs, producing pressure losses;

• Eliminating the critical portions of the good adduction by changing the pipeline route or joining them with other addictions that do not have such obstacles;

• Regular cleaning of the intakes by feeding them to collection containers, using nitrogen, or washing them with water jets in cases of accumulated solid deposits.

5. Conclusions

In this paper we introduced a new methodology to depleted gas rehabilitation.

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