Calculation of the Optimal Gas Flow Rate Under Conditions of Sand Plug Formation

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Abstract. The development and operation of gas and gas condensate fields in Western Siberia is associated with a number of serious problems associated with the aging of the fields. One of these problems is the formation of sand plugs at the bottom of the well, which leads to a halt in production and the need for repairs. To solve this problem, it is necessary to correctly calculate the optimal well flow rate, taking into account the filtration resistance and pressure losses along the wellbore. The construction of an adequate mathematical model of fluid filtration in the conditions of sand plug formation will make it possible to correctly regulate the flow rate of the well and avoid complications in its operation.

1. Introduction

The main complications during the operation of gas wells include:

- drop in reservoir pressure;
- lifting the gas-water contact to the perforation intervals of production wells;
- formation of sandy-clay plugs at the bottom of wells;
- sandblasting, i.e. intensive gas production with an overestimated flow rate, etc.

As a result of a combination of factors, there is a decrease in gas flow rate and, as a result, a decrease in the level of production in the field as a whole. In this situation, the subsoil user is forced to carry out capital repairs of production wells, which reduces the turnaround time and leads to unplanned production shutdowns, and thereby increases economic losses and additional costs for field development.

In this regard, it is necessary to determine the optimal well operation mode (gas flow rate), which will reduce the formation of a sand plug and, on the other hand, will not cause excessive, intensive wear of the inner surface of the production string, which ultimately leads to behind-the-casing losses of liquid and gas. That is, it will thereby allow maintaining the production level at the proper level without negative, aggravating consequences.

2. Methods

Let us consider the calculation of the optimal operating mode using the example of one of the wells of gas fields in Western Siberia [3].

Figure 1 shows the dynamics of changes in cumulative gas production depending on the operating period of well N, both taking into account the overhaul and without interrupting gas production.
As can be seen from the graph, over the entire period of operation, the well was shut-in twice to perform workover operations. Losses from forced shutdowns of gas production amount to 38 million m³, which was determined by modeling the non-stop operation of the well and its discrepancy with the actual production value.

According to the results of gas-dynamic studies of this well, the identified shutdowns were caused by the formation of a sand plug at the bottomhole.

![Graph showing cumulative gas production](image)

**Figure 1.** Dynamics of changes in cumulative gas production.

Thus, both for this well and for most similar wells, increasing the turnaround time is a rather urgent task. To achieve this, it is necessary to determine such a gas flow rate that would allow not only to maintain the production level, but also to reduce the effect of the sand plug on the well productivity.

For a more detailed presentation of the optimal well operation mode, we will schematically analyze the entire process of fluid filtration in a vertical gas well bore partially filled with sand (Figure 2).
Figure 2. Filtration of fluid in a vertical gas wellbore partially filled with sand.

As can be seen from the above figure, to calculate the optimal flow rate, the wellbore must be divided into two sections:

- The first section is a space filled with sand;
- The second section is the trunk free of sand.

For each section, it is necessary to calculate the main parameters such as the fluid filtration rate for each perforation, hydraulic resistance and pressure loss along the wellbore. Then calculate the flow rate of the well.

3. Results and Discussion
Suppose the composition of the gas is known (Table 1), on the basis of which it is initially required to determine the physicochemical properties of the gas, and the current operating mode of the well is also given (Table 2).

| №  | Name of the component | Percentage of the component |
|----|-----------------------|-----------------------------|
| 1  | CH₄                   | 0,741                       |
| 2  | C₂H₆                  | 0,075                       |
| 3  | C₃H₈                  | 0,034                       |
| 4  | i-C₄H₁₀               | 0,008                       |
| 5  | n-C₄H₁₀               | 0,017                       |
| 6  | i-C₅H₁₂               | 0,006                       |
| 7  | n-C₅H₁₂               | 0,003                       |
| 8  | C₆H₁₄                 | 0,006                       |
| 9  | N₂                    | 0,061                       |
| 10 | H₂S                   | 0,020                       |
| 11 | CO₂                   | 0,030                       |
Table 2. Current well operation mode.

| №  | Parameter                        | Value |
|----|----------------------------------|-------|
| 1  | Gas flow rate, thousand m³/day   | 350   |
| 2  | Reservoir pressure, MPa          | 7     |
| 3  | Reservoir temperature, K         | 300   |
| 4  | Pipe diameter, m                 | 0.102 |
| 5  | Number of perforations, units    | 100   |
| 6  | Distance between perforations, m | 3     |

As a result of mathematical calculations, we obtain the following parameters, which are necessary to determine the Reynolds number and hydraulic pressure loss:

- density in reservoir conditions is 74.18 kg / m³;
- relative density - 0.76 kg / m³;
- the value of the supercompressibility coefficient is 0.85 unit fractions;
- the dynamic viscosity of the gas is 0.0145 mPa · s.

The Reynolds number determines the nature of the gas flow in the perforation interval between the holes, which affects the value of the emerging hydraulic resistance.

Consider the case when the wellbore is not filled with sand (Figure 3).

The well under consideration, like most in Western Siberia, has a perforated bottomhole. In our case, the density of perforations is 100 units. at 300 m. The gas inflow along the bottomhole profile is heterogeneous, and therefore, in each section between the holes, different values of hydraulic resistance arise, which directly affect the productivity of the well.

![Figure 3](image_url)

**Figure 3.** Scheme of fluid movement in the section of the wellbore free from sand.

In addition to calculating the hydraulic resistance of the flow, it is necessary to calculate the pressure loss for each perforation hole.

- at the level of the perforation (k-th) hole:

  \[ P_{2k-2}^{bc} \cdot \frac{P_{2k-1}^{bc}}{P_{2k-2}^{bc} - P_{2k-1}^{bc}} = \frac{\lambda_2 \left( \sum_{i=j}^{k-1} m_i \right) ZRTL_2}{F D} \frac{1 - e_{2k-2}^{bc}}{b} , \]  

(1)

- after the perforation (k-th) hole:
where \( L_1 \) - is the distance between the holes, \( m \); \( L_2 \) - length of the section with holes, \( m \); \( b \) - constant, \( R \) - universal gas constant (\( J / \text{kg K} \)); \( T \) - flow temperature, \( K \); \( F \) - cross-sectional area of the pipe, \( m^2 \); \( D \) - pipe inner diameter, \( m \); \( Z \) - coefficient of supercompressibility of gas, \( \lambda_1 \) - hydraulic resistances in the area with perforations, \( \lambda_2 \) - hydraulic resistances in the area without perforations.

As you know, when gas flows in a pipe, the flow rate increases, therefore, when calculating pressures in the wellbore, it is necessary to take into account the fluid flow regime [4]. Accordingly, when calculating the hydraulic resistance between perforations and in the areas between perforation intervals, the flow regime should be taken into account:

\[
\lambda = \frac{A}{Re^m},
\]

where \( Re \) is the Reynolds number.

The quantities \( A \) and \( m \) take on different values depending on the well operation mode (laminar, critical, turbulent, quadratic resistance zone).

Another case that needs to be considered is a sand filled shaft (Figure 4).

![Figure 4. Scheme of fluid movement in the section of the borehole filled with sand.](image-url)
The un-known size of the sand plug in real conditions only further complicates the definition of a qualitative, mathematical model of the well operation. Knowledge of the plug parameters and its behavior when the bottomhole pressure changes is a key indicator of the successful selection of the optimal well operation mode.

The presented mathematical models for calculating hydraulic pressure losses during gas filtration under different conditions mainly depend on the mass flow rate that falls on each inflow point, as well as on its accumulation during gas movement from the bottomhole to the upper perforation interval.

The drawdown for each perforation from the formation side is calculated based on the following formula [4]:

$$\Delta P_i = \sum_{j=1}^{n} \frac{m_j \mu}{8\pi h k \chi_z} \int_0^1 \sum_{m=0}^{\infty} \left\{ \exp \left[ \frac{(x_j - x_i)^2}{4 \chi_t} + \frac{(z_j - z_i + 2nh)^2}{4 \chi_z} \right] + \exp \left[ \frac{(x_k - x_i)^2}{4 \chi_t} + \frac{(z_k + z_i + 2nh)^2}{4 \chi_z} \right] \right\} dt,$$

where $\Delta P_i = (P_{m} - P_{w})_i$ is the depression for the Leibenson function for the $i$-th hole, $m_j$ - mass flow rate of the $j$-th hole, kg/s.}

The distribution of pressure losses along the wellbore with a uniform distribution of the flow rate over the perforated interval of the investigated well is shown in Figure 5.

The presented mathematical models for calculating hydraulic pressure losses during gas filtration under different conditions mainly depend on the mass flow rate that falls on each inflow point, as well as on its accumulation during gas movement from the bottomhole to the upper perforation interval.

The un-known size of the sand plug in real conditions only further complicates the definition of a qualitative, mathematical model of the well operation. Knowledge of the plug parameters and its behavior when the bottomhole pressure changes is a key indicator of the successful selection of the optimal well operation mode.
Unfortunately, the necessary information is constantly not enough, on the basis of which it would be possible to draw a conclusion about the nature and degree of formation of the sand plug. As a result, in most cases, when creating a mathematical model, the height of the plug is assumed to be conditional, which introduces a significant error in the calculations.

Another option for solving this problem is the use of iterative calculation, as a result of which the inflow volume of each hole is determined with the selection of the most probable size of the sand plug, so that the total inflow corresponds to the well flow rate in the studied operating mode.

As a result of applying this approach, we will obtain an estimate of the condition at the bottomhole with a much smaller error.

4. Conclusion
In this regard, to achieve this goal, namely modeling and analysis of the optimal well operation, the following is necessary:
- stable operation of the well, for high-quality adaptation of the model;
- the field of permeability of working interlayers / formation along the "well-formation" contact in the perforation interval, which is required to calculate the gas flow to the holes;
- sand plug assessment, as a result of iterative calculation of the model;
- inflow profile, as a consequence of the gas flow velocity profile in the perforation interval, which is required to calculate pressure losses;
- the value of the filtration coefficients a and b based on the results of gas testing and well testing, a maximum of 2-3 years ago, which is required for a control check of the tuned mathematical model and estimation of reservoir pressure.

As a result of sequential data interpretation and parameter calculation, we will obtain a full-fledged mathematical model of the investigated well operation.

This concept for well performance analysis is multipurpose, which, mainly, leads to simplification of well operation control and immediate prevention of many undesirable, negative consequences from its long-term operation.

Figure 5. Dynamics of changes in hydraulic losses in the wellbore.
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