Water and gas mixture characteristics calculation and its possible injection variants

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Abstract. The aim of this article is the practical application of calculation methodology of water and gas volume injection into the reservoir and optimal parameters of water and gas mixture in Samodurovskoe field in Russia. Calculations were performed using two technologies: water alternating gas (WAG) and simultaneous water and gas injection (SWAG). For each case the optimum volume of water and gas mixture and its components which are injected into the reservoir was calculated. The variant of alternative water and gas injection cannot be applied in oilfield because of existing restriction to maximum flowrate of associated gas in standard conditions. In Samodurovskoe field can be applied water-alternated-gas (WAG) technology. Proper array of gas and water ration phases in reservoir condition with account of associated gas usage was calculated. Optimization of water-gas mixture volume ratio components showed that the biggest effectiveness of oil recovery cannot be reached resulting from abovementioned restriction. This calculation methodology can be used in job execution, it is simple and practical.

1. Introduction

The methods of enhanced oil recovery, practical usage of associated gas, ecological safety are essential problems of present-day oil industry in Russia and abroad. For today there is a tendency to deterioration of oil field development conditions, it relates to depletion of reservoir with easily recoverable oil reserves. In such conditions conventional flooding won’t be effective. For this reason, the interest grows to use technologies which increase effectiveness of field development such as alternated-gas injection (WAG and SWAG) [1-12]. To estimate effectiveness of this technology and practical application the appropriate calculations should be made. There are three variants of alternated-gas injection implementation:

- Variant 1. Long water alternating gas (WAG).
- Variant 2. Alternate water alternating gas (WAG).
- Variant 3. Simultaneous water and gas injection (SWAG).

2. Materials and methods

Calculations of optimal parameters for the implementation of WAG, the optimal volume of water-gas mixture pumped into the reservoir and its constituents (water and gas phases) were carried out according to the methods described in the monograph [1] with the change of symbols of some variables. The calculated data on the Samodurovskoye field were taken from the work [2], also by the procedure from this work the bottom-hole pressure of injection well was calculated. In techniques several generally accepted formulas for more closer definition of calculations were added.

3. Results

The data for calculation for the Samodurovskoye field is presented in table 1.

| Parameter | Designation | Measure | Value |
|-----------|-------------|---------|-------|

Table 1 The data for calculation for the Samodurovskoye field
A number of injection wells  $N_{kv}$  w.  11
A well depth  $H_{kv}$  m.  1796.6
An inner diameter of production string  $D_{in}$  m.  0.06
A water flow in the injection well during the implementation of the reservoir pressure maintenance system using conventional technology  $Q_{kv}$  m$^3$/d  130
A volume of water injected into the reservoir during the implementation of the reservoir pressure maintenance system using conventional technology  $Q_{VVGVpl}$  m$^3$/d  1535
A reservoir pressure  $P_{pl}$  MPa  16
An injection wellhead temperature  $T_y$  K  268
An injection bottom-hole temperature  $T_{sub}$  K  304
A reservoir temperature  $T_{pl}$  K  306
A reservoir density of oil  $\rho_{n\text{-}pl}$  kg/m$^3$  854
A density of oil in standard conditions  $\rho_n$  kg/m$^3$  863
A water-mass density in reservoir conditions  $\rho_v\text{-}pl$  kg/m$^3$  1158
A water-mass density in standard conditions  $\rho_v$  kg/m$^3$  1161
A gas density in standard conditions  $\rho_g$  kg/m$^3$  1.15
A formation volume factor  $B_o$  unit fraction  1.030
A gas oil ratio  $G$  m$^3$/t  18.9
A maximum value of the flow of associated gas in standard conditions  $Q_{g\text{-}max}$  m$^3$/d  60274

### 3.1. Calculation of optimal parameters for the implementation of WAG

In the implementation of WAG on the current site to compensate for the selection, is adopted by the existing reservoir pressure maintenance system, the volume of pumped water, which, in terms of gas, in reservoir conditions, will be

$$Q_{gV\text{VGV}} = b_{v\text{-}pl} Q_{VVGV} , \text{ m}^3/\text{d}.,$$

where $b_{v\text{-}pl}$ – the coefficient of cubic expansion of water, in reservoir condition $b_{v\text{-}pl} \approx 1$,

$$Q_{gV\text{VGV}} = Q_{VVGV} .$$

The volume of the injected gas in standard conditions is determined from the formula

$$Q_{gV\text{VGV}} = \frac{Q_{VVGV}}{b_{v\text{-}pl} \rho_{pl} \bar{z}_{pl}} , \text{ m}^3/\text{d}.,$$

(1)

where $Q_{VVGV}$ – the volume of water injected into the reservoir during the implementation of the reservoir pressure maintenance system using conventional technology in standard conditions, m$^3$/d;
Рпл – reservoir pressure, МПа; Тпл – reservoir temperature, К; Р and Т – pressure and temperature in standard conditions, Р = 0.1 МПа, Т = 293 К; Zпл – z-factor in reservoir conditions.

By placing the T1 reservoir basic data we will get

\[ Q_{gV VG} = \frac{1535 \times 16 \times 293}{0.1 \times 306 \times 0.8179} = 287524 \text{ m}^3/\text{d}. \]

To determine Zпл can be used approximation formulas of P.D. Lyapkov:

\[ P_{pr} = \frac{P}{P_{kr}} = \frac{16}{4.5} = 3.5 \text{ , MPa}, \]

\[ T_{pr} = \frac{T}{T_{kr}} = \frac{306}{190.7} = 1.6 \text{ , K}, \]

for 0 < P_{pr} ≤ 3.8 and 1.17 ≤ T_{pr} < 20

\[ Z_{pr} = 1 - P_{pr} \left[ \frac{0.18}{T_{pl} - 0.73} - 0.135 \right] + \frac{0.016 \rho_{pr}^{3.45}}{T_{pr}^{1.61}}, \]

\[ Z_{pr} = 1 - 3.5 \times \left[ \frac{0.18}{1.6 - 0.73} - 0.135 \right] + 0.016 \times \frac{3.45^{3.45}}{1.61} = 0.8179. \]

The resulting volume of gas does not correspond to the maximum allowable value of the volume injected into the reservoir \( Q_{gV VG} > Q_{g max} \), therefore this embodiment of the WAG is not suitable.

In implementing WAG technology essential injection well head pressure is:

\[ P_y = \sqrt{\frac{P_{zab}^2 - \theta Q_{gV VG}^2}{\varepsilon^2 S}}, \text{ MPa}, \quad (2) \]

where \( P_{zab} \) – bottomhole pressure of the injection well, MPa; \( Q_{gV VG} \) – gas flow in standard conditions, m\(^3\)/d., determine from (1); \( \theta \) – parameter, from formula:

\[ \theta = 1.19 \times 10^{-6} \lambda S_{sr}^2 T_{sr}^2 \left( \frac{e^{2S} - 1}{e} \right) D_{vn}^{-5}, \quad (3) \]

where \( D_{vn} \) – inner diameter of production string, м; \( \lambda \) – hydraulic resistance coefficient of gas current in production string, accepted \( \lambda = 0.025 \); \( e \) – base of the natural logarithm, \( e = 2.7 \); \( S \) – dimensionless parameter, by formula:

\[ S = \frac{0.0314 \rho_g H_{skv}}{Z_{pl} T_{sr}}, \quad (4) \]

where \( \rho_g \) – gas relative density:

\[ \rho_g = \frac{\rho_{n pl} B_{a} - \rho_n}{G}, \]

where \( H_{skv} \) – well depth, м; \( T_{sr} \) – average temperature, К, determined as:

\[ T_{sr} = \frac{(T_y + T_{zab})}{2}, \text{ K}. \]

Offered calculation methodology allows to determine the optimal volume of gas and its pressure on wellhead, providing its injection into reservoir in this volume and use this data to assess the optimal volume and time limits of the technology implementation.

3.2. The method of calculating the optimal volume of injected into the reservoir water-gas mixture and its components (water and gas phases) during the implementation of SWAG [1]

Effective oil displacement will be done in case of gas and water ration phases in reservoir under the condition:
\[ k_{VG\,pl} = \frac{Q_{v\,VG\,pl}}{Q_{v\,VG} \cdot \frac{P_{pt}}{P_{pt\,pl}}} = 0.2 \div 0.5. \]

A calculation is made by next formulas:

\[ Q_{v\,VG\,pl} = \frac{\dot{Q}_{ev\,comp}}{1 + k_{VG\,pl}}, \text{ m}^3/\text{d}, \quad (5) \]

\[ Q_{g\,VG\,pl} = Q_{comp} - Q_{v\,VG\,pl}, \text{ m}^3/\text{d}, \quad (6) \]

\[ Q_{g\,VG} = Q_{g\,VG\,pl} \frac{P_{pt\,pl}Z_{pl}}{P_{pt}\,Z_{pl}}, \text{ m}^3/\text{d}. \quad (7) \]

In implementing SWAG at the site of the Samodurovsky field under this condition \( k_{VG\,pl} = 0.2 \):

- injected water consumption by (5)

\[ Q_{v\,VG\,pl} = \frac{1535}{1 + 0.2} = 1279.2 \text{ m}^3/\text{d}, \]

- consumption of injected gas under SWAG in reservoir conditions by (6)

\[ Q_{g\,VG\,pl} = 1535 - 1279.2 = 255.8 \text{ m}^3/\text{d}, \]

- consumption of injected gas under SWAG in standard conditions by (7)

\[ Q_{g\,VG} = 255.8 \times \frac{16 \times 293}{0.1 \times 306 \times 0.8179} = 47914.5 \text{ m}^3/\text{d}. \]

Under \( k_{VG\,pl} = 0.3 \):

- injected water consumption by (5)

\[ Q_{v\,VG\,pl} = \frac{1535}{1 + 0.3} = 1180.8 \text{ m}^3/\text{d}, \]

- consumption of injected gas under SWAG in reservoir conditions by (6)

\[ Q_{g\,VG\,pl} = 1535 - 1180.8 = 354.2 \text{ m}^3/\text{d}, \]

- consumption of injected gas under SWAG in standard conditions by (7)

\[ Q_{g\,VG} = 354.2 \times \frac{16 \times 293}{0.1 \times 306 \times 0.8179} = 66346 \text{ m}^3/\text{d}. \]

Under \( k_{VG\,pl} = 0.4 \):

- injected water consumption by (5)

\[ Q_{v\,VG\,pl} = \frac{1535}{1 + 0.4} = 1096.4 \text{ m}^3/\text{d}, \]

- consumption of injected gas under SWAG in reservoir conditions by (6)

\[ Q_{g\,VG\,pl} = 1535 - 1096.4 = 438.6 \text{ m}^3/\text{d}, \]

- consumption of injected gas under SWAG in standard conditions by (7)

\[ Q_{g\,VG} = 438.6 \times \frac{16 \times 293}{0.1 \times 306 \times 0.8179} = 82155.1 \text{ m}^3/\text{d}. \]

Under \( k_{VG\,pl} = 0.5 \):

- injected water consumption by (5)

\[ Q_{v\,VG\,pl} = \frac{1535}{1 + 0.5} = 1023.3 \text{ m}^3/\text{d}, \]

- consumption of injected gas under SWAG in reservoir conditions by (6)

\[ Q_{g\,VG\,pl} = 1535 - 1023.3 = 511.7 \text{ m}^3/\text{d}, \]

- consumption of injected gas under SWAG in standard conditions by (7)

\[ Q_{g\,VG} = 511.7 \times \frac{16 \times 293}{0.1 \times 306 \times 0.8179} = 95847.6 \text{ m}^3/\text{d}. \]

Summary data of calculations is represented in the table 2.

| Parameters | Value when \( k_{VG} = Q_{v\,pl} / Q_{v} \) |
|------------|--------------------------------------------|
|            |                                            |
The volumes of components of the water-gas mixture injected into the reservoir:
- a water in reservoir conditions, m\(^3\)/d.: 1535, 1279.2, 1180.8, 1096.4, 1023.3
- a gas in standard conditions, m\(^3\)/d. million.: 0, 47914.5, 66346, 82155.1, 95847.6

Taking into account maximum value of the flow of associated gas in standard conditions \(Q_{g,\text{max}} = 60274\) m\(^3\)/d., it can be concluded that Effective oil displacement will be done in case of gas and water ration phases in reservoir condition in a range of \(0.2 \leq k_{VGV,pl} \leq 0.265\).

3.3. The calculation of the pressure at the bottom of the injection well.

\[
P_{zab} = (P_y + \rho_v g H_{skw} - \Delta P_{tr}) \times 10^{-6} , \text{ MPa}, \tag{8}
\]

\[
\Delta P_{tr} = \frac{H_{skw} V^2}{2 \times 10^6 d_m} \rho_u , \text{ MPa}, \tag{9}
\]

where \(\lambda\) – hydraulic resistance coefficient, determined by Altshul formula

\[
\lambda = 0.11 \left( \frac{68}{Re} + \frac{\Delta}{d_m} \right)^{0.25} , \tag{10}
\]

\(Re\) – Reynolds number

\[
Re = \frac{V d_m \rho_u}{\mu_v} , \tag{11}
\]

\(V\) – water velocity in production string

\[
V = \frac{4 Q_{skw} v}{86400 \pi d_m^2} , \text{ m/s}, \tag{12}
\]

\(\mu_v\) – dynamic viscosity of stratum water, Pa*s. It can be determined by P.D. Lyapkov’s formula [2]

\[
\mu_v = \frac{0.0014 + 38 \times 10^{-7} (\rho_v - 1000)}{10^{0.065 x^2}} , \text{ Pa*s}. \tag{13}
\]

Calculations of friction pressure drop will be made. At first, \(\mu_v\) will be found by formula (13), by taking temperature equal to \(t = 20\) ºC.

\[
\mu_v = \frac{0.0014 + 38 \times 10^{-7} (1158 - 1000)}{10^{0.065 \times 29}} = 1.48 \times 10^{-3} \text{ Pa*s}.
\]

Therefore, \(\mu_v = 0.0014 + 38 \times 10^{-7} (1158 - 1000) = 1.48 \times 10^{-3} \text{ Pa*s}\).

Calculate \(V\) by formula (12)

\[
V = \frac{4 \times 130}{86400 \times 3.14 \times 0.06^2} = 0.5324 \text{ m/s}.
\]

Reynolds number by formula (11)

\[
Re = \frac{0.5324 \times 0.06 \times 1158}{1.48 \times 10^{-3}} = 24994 .
\]

Hydraulic resistance coefficient by formula (10), taking the value of \(\Delta = 0.003\) m

\[
\lambda = 0.11 \left( \frac{68}{24994} + \frac{0.003}{0.06} \right)^{0.25} = 0.05271 .
\]

Substitute the value in formula (9), friction pressure loss will be found \(\Delta P_{tr}\)

\[
\Delta P_{tr} = 0.05271 \times 1796.6 \times 0.5324^2 = 0.2590 , \text{ MPa}.
\]
Bottom hole pressure $P_{zab}$ in injection well will be found by (8)

$$P_{zab} = (9.5 + 1158 \times 9.81 \times 1796.6 - 0.2590) \times 10^{-6} = 20.4 \text{ MPa}.$$ 

To determine pressure on wellhead in implementation of SWAG, calculations of generalized hydrodynamic pressure gradient in production string

$$P_y = P_{zab} - \sum_{i=1}^{m-1} \frac{dp}{dh} h_{sh} \text{, MPa},$$

where $(dp/dh)_n$ – generalized hydrodynamic pressure gradient in the 1st calculated section of tubing, MPa/m; $h_{sh}$ – calculation step, m; $m$ – any calculated section or number of calculated sections in production string from 1 to $P_{zab}$ – bottom hole pressure in injection well, MPa.

### 3.4. Optimization of water-gas mixture volume ratio components, which is injected in a reservoir in implementation of WAG or SWAG

Density of water-gas mixture, which is injected in volume of injection to withdrawal ratio in reservoir conditions, is determined by formula:

$$\rho_{GV} = \left( \rho_g p_t \frac{Q_g V}{Q_g V_t} + \rho_{v} p_t \frac{Q_v V}{Q_g V_t} \right) / \rho_{sm V} p_t \text{, kg/m}^3,$$

where $\rho_{v} p_t$ – water density in reservoir conditions, kg/m$^3$, is allowed to equal water density in standard conditions, that is $\rho_{v} p_t = \rho_v$; $\rho_{v} p_t$ – density of hydrocarbon gas in reservoir conditions will be found next:

$$\rho_{g} p_t = \rho_{g} \frac{p_{pl}^T}{p_{pl}^T p_{g}^T}, \text{ kg/m}^3,$$

$$\rho_{g} p_t = 1.15 \frac{16.293}{0.01 \times 306 \times 0.8179} = 215.4 \text{ kg/m}^3,$$

substitute the value $\rho_{g} p_t$ in formula (15), the density of water-gas mixture will be found

$$\rho_{GV} = \frac{215.4 \times 255.8 + 1161 \times 1279.2}{1535} = 1003.4 \text{ kg/m}^3,$$

$$\rho_{GV} > \rho_{p} p_t.$$

Water-alternated-gas injection effectiveness increase can be achieved by means of usage of this technology in the quality of water-gas mixture displacement working agent in density equal to the oil which is displaced in reservoir conditions

Density of water-gas mixture in reservoir conditions, which is equal to the oil which is displaced in reservoir conditions, is achieved by the means of providing in the flow of consumption:

- gas in reservoir conditions, determined by formula which is received by the way of solution relative to $Q_{g V} V V_{G V} p_t$, trying to find $\rho_{GV} p_t = \rho_{n} p_t$

$$Q_{g V} V V_{G V} p_t = \frac{Q_{sm V} p_t (\rho_{g} p_t - \rho_{n} p_t)}{\rho_{p} p_t - \rho_{g} p_t}, \text{ m}^3/d.,$

$$Q_{g V} V V_{G V} p_t = \frac{130 \times (1161 - 854)}{1161 - 215.4} = 42.2 \text{ m}^3/d.,$$

- water in reservoir conditions, determined by formula:

$$Q_{w V} V V_{G V} p_t = Q_{sm V} p_t - Q_{g V} V V_{G V} p_t, \text{ m}^3/d.,$$

where $Q_{sm V} p_t$ – consumption of water-gas mixture, which is injected in a reservoir in the process of WAG implementation, in reservoir conditions, m$^3$/d., accepted $Q_{sm V} p_t \approx Q_{G V comp}$, $\rho_{v} p_t$ – density of water in reservoir conditions, kg/m$^3$, assume that $\rho_{v} p_t = \rho_v$; $\rho_v$ – density of water in standard conditions, kg/m$^3$. 


\[ k_{VGVpl} = \frac{Q_{gVGVpl}}{Q_{vVGVpl}} = \frac{42.2}{87.8} = 0.48. \]

That is as \( k_{VGVpl} = 0.48 \) maximum effectiveness of water-alternated-gas injection will be achieved.

4. Discussion

Usage of alternated-gas injection has remarkable advantages over other advanced recovery methods:

- increasing of conformance factor and oil recovery factor;
- rational utilization of associated gas.

With the purpose of successful practical usage of this technology, it is necessary to calculate volumes of water and gas injected into the reservoir, determine the appropriate injection option. That’s the reason of necessity in selecting a convenient method of such parameter’s calculation. The data which was obtained in the present article shows the ability of described methodology usage and the possibility of water-alternated-gas (WAG) technology realization in Samodurovskoe field.

Conclusions

For conditions of different reservoirs is necessary to select optimum parameters while injecting water and gas. Proceeding from Samodurovsky field calculations, next conclusions can be made:

- volume of gas consumption in alternative injection of water and gas in reservoir falls short of maximum flowrate condition of associated gas in standard conditions;
- taking into account that \( Q_{g_{max}} = 60274 \text{ m}^3/\text{d} \), effective oil displacement will occur in correlation of gas and water phases in reservoir conditions ranging from 0.2 to 0.265.

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