Hydrodynamic analysis of the efficiency of thermochemical methods at deposits with complicated development conditions

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Abstract. In this paper we will focus on a promising technology of thermochemical treatment using the energy of the exothermic reaction of the interaction of two inorganic salts pumped into the reservoir in the form of an aqueous solution. The technology is environmentally safe and effective for intensification of production at low-yield wells of "old" layers and for low-permeable layers of unconventional high-viscosity oil. The authors created a mathematical model of the process and conducted a series of numerical studies that form the basis of field experiments to test technology at various fields in Russia. This work was supported by the RFBR grant No. 19-07-00433 A.

1. Introduction
The technology of thermal-gas-chemical formation treatment (TGCT) on hydrocarbon deposits has been known for about 60 years. Initially, this process was organized by introducing an explosive into the reservoir and initiating a combustion reaction by electrical discharge through an electrical cable to the bottom of a well. When initiating the reaction took less than one second, the process of decomposition began with the release of gas due to which there was an impulse, followed by increased pressure and temperature in the bottom hole zone [1]. Nowadays, TGCT technology is focused on creation of in-reservoir increased pressure-temperature zones, which means that technology refers to EOR methods rather than methods of stimulating production, as it increases the inflow rate and, in some cases, even allows producing oil from reservoirs with low permeability, complex structure and low fluid mobility.

2. Basic principles and application experience
The main impact on the deposit occurs due to high pressure waves and heat waves arising from the exothermic decomposition reaction of the COC in a porous space, accompanied by significant heat and gas release. Gas release provokes a rapid pressure rise in the localized zone of active substances, which leads to structural changes in the matrix frame in the bottom hole formation zone, changes in porosity and permeability, the transition of fixed hydrocarbons in the fluid state due to fluid viscosity reducing, as well as to changes in the saturation filtration characteristics of phases and components fluids saturating the deposit. Levels of pressure and temperature changes are different: according to the bottom hole parameters hydrodynamic control the temperature in the bottom hole zone and at the remote area of the well changes by 30-40 % avg, and the reservoir pressure – by 200-300% as a result of the field studies. When exceeding the threshold pressures (depending on deposit type) due to the sharp release of the decomposition products of the COC, the formation of additional fracturing occurs,
the level of effective permeability increases, and the value of residual oil saturation decreases. The ultimate pressures values in the reaction zone, the decomposition rate and energy release depend on the BM concentration in water solution, reaction retarder and the volume of washer before applying the reaction activator [3].

Initially, technology involves the delivery of solid activator of the reaction in the formation with proppant stimulation for further COC decomposition reaction during fracturing. Granular magnesium was originally used as an activator.

The main purpose of such a process in fractured wells is to extend the distance between wellbore and active components reaction zone. This method of wells treatment was tested in several fields in Russian Federation and resulted in increased inflows in the wells obtained after treatment, however two wells resulted with uncontrolled treatment progression with pressure surge. Authors of this paper have studied the problem. For this purpose a team of authors from Gubkin Russian State University of Oil and Gas (RIU) developed a mathematical model [4], numerical experiments were conducted and origins of pressure surge were identified. The authors assume that the main problem of the current situation was the incomplete transportation of the solid reaction activator to the remote crack zone and insufficient cleaning of granular particles of the activator out the borehole, as these particles started the reaction in bottom hole zone during COC injection instead of planned reaction zone.

Confirmation of delay of magnesium particles besides the casing (at the Usinskoye field) led to the rejection of solid activator usage towards safer methods. The last patent number 2696714 as of 2019 regiments separate supply (via different channels) of exposure active substances. At the same time, work on TGCT is carried out using binary mixtures (BM), which include a water solution of inorganic salts and special reaction retarders. The exothermic reaction of the working composition is two-stage [3]:

\[
\text{NH}_4\text{NO}_3 + \text{NaNO}_2 \leftrightarrow \text{NH}_4\text{NO}_2 + \text{NaNO}_3, \quad (1)
\]

\[
\text{NH}_4\text{NO}_2 + \text{H}^+ \rightarrow \text{N}_2 + 2\text{H}_2\text{O} + 300 \text{ kJ/mole}. \quad (2)
\]

Ammonium nitrite, formed during the reversing reaction (1), is easily decomposed into nitrogen and water under the action of acid catalysts. The result of this reaction generates heat as of 4688 kJ/kg. Reaction (2) shifts the equilibrium in reaction (1) to the right and thus reaction (2) can be brought to an end as follows:

\[
\text{NH}_4\text{NO}_3 + \text{NaNO}_2 \rightarrow \text{N}_2 + \text{NaNO}_3 + 2\text{H}_2\text{O} + 300 \text{ kJ/mole} \quad (3)
\]

The use of BM expands the range of wells applicable for treatment because it is safe, and therefore possible to run at non-fractured wells. The technology of TGCT with BM application is carried out by successive BM injection into deposit, as well as BM decomposition reaction activator, reaction retarder, washer and fracturing fluid (Fig.1,a). Reaction retarders suspend the reaction and this allows to inject the required volume of fracture fluid into the deposit which separates the reaction zone out of the bottom hole zone. Properties of the working mixture depend on the state of the field in time of processing (porosity, permeability, reservoir heterogeneity, anisotropy properties, clogging degree, field watercut, gas factor). Selection of the volumes of injected agents, and BM concentration is made on the basis of hydrodynamic researches of wells-candidates. Variation of the parameters in the reaction zone occurs by changing the concentration of the solution, the inject sequence of the components of the working mixture. Currently the technology is underway to expand its infusion.

Table 1 presents a summary of TGCT technology application in some wells of different fields in Russian Federation. Some of them resulted to long-term effect, thus additional production of more than 2000 tons of oil was obtained.
Table 1. Treatment with technology TGCT BM.

| Object of treatment with TGCT BM technology | Before treatment | After treatment | Current values (January 2019) | Additional oil production | Confirmed duration of effect |
|---------------------------------------------|------------------|----------------|-----------------------------|--------------------------|-----------------------------|
| Oil well No.1 (2017)                        | 0.5              | 5.7            | -                          | -                        | No data                     |
| Oil well No.2 (2017)                        | 2.5              | 5.0            | -                          | -                        | No data                     |
| Oil well No.3 (2017)                        | 0                | 3.14           | 1.51                       | 701                      | 12 months                   |
| Oil well No.4 (2017)                        | 1.93             | 7.4            | 5.1                        | 2051                     | 12 months                   |
| Oil well No.5 (2017)                        | 1.4              | 10.0           | 5.6                        | -                        | 12 months                   |
| Oil well No.6 (2018)                        | 0.5              | 2.7            | 2.6                        | -                        | 3 months                    |
| Oil well No.7 (2018)                        | 1.5              | 1.8            | 4.3                        | -                        | 3 months                    |

3. TGCT Hydraulic simulation

Authors used hydrodynamic simulation as a tool for preliminary reservoir properties assessment in the zone near applicable wells and for online process support during field experiments. TGCT preparation is a complex process that leads to a significant change in the thermodynamic state of the reservoir system, and therefore it must be accompanied by calculations on an adapted hydrodynamic model. The authors of the work carried out calculations using their own mathematical model as of 2009 [5]. In the latest work in simulation the impact of binary mixtures calculations were carried out in several stages:

1. assessment of the current state of the reservoir system (taking into account the parameters of production and well tests);
2. calculation of the agents injection zone (according to the processing record and well injection capacity data);
3. calculation of high pressure and temperature zone (including influence of the impact of all reagents injected into the deposit);
4. the development of the deposit reaction and relaxation (taking into account the of pressure and temperature control data).

The first stage includes comparison of calculated filtration processes in reservoir hydrodynamics model with the current data on its state obtained from the field. To approximate the model to the real deposit conditions, the estimated porosity and permeability, pressure and current production rate were compared. Adaptation calculations determined the deposit clogging degree, the actual skin factor and reservoir characteristics. On the second stage after adaptation estimated volumes of all liquids (BM, washer, activator, retarder) were injected.

The mathematical model is based on the principles of mechanics of interpenetrating continua with the assumption of the generalized Darcy laws for each phase of a multiphase monopartite mixture linearity (only macroscopic velocities were considered without diffusion processes). The model responses to phase transitions as well as the structure of the reservoir and the anisotropy of the reservoir overall. At the first and second stages of the calculation, the flow is reviewed in a two-dimensional formulation (in cylindrical coordinates), but considering zonal inhomogeneity at the bottom hole zone. At the first two stages, phases were considered as inert to each other, there were no phase transitions (due to the reaction retarder diffusion), and no changes in the reservoir properties. At these stages the conditions of zero intensities of mass transfer between the phases of Jji and the absence of changes in the structure of the porous space in the common equations set were imposed.

The phases continuity equations in accordance with the classical theory of multiphase and multi-speed continuum are as follows:

\[
\frac{\partial (\rho_j^o s_i m)}{\partial t} + \text{div} \left( \rho_j^o s_i m \vec{v}_j \right) = \sum_j J_{ji}
\]

where \( m \) – porosity; \( s_i \) – i-phase porous space saturation; \( \rho_j^o \) – i-phase true density; \( \vec{v}_i \) – i-phase mass-averaged velocity; \( J_{ij} \) – mass transient intensity from i-phase to j-phase.
In subsequent stages, the equations of state are supplemented by equations for the mass concentrations of active components in a water solution, which velocities correspond to the water phase velocity.

To write the equations of motion, the generalized Darcy's law is used, in which the phase pressures are taken equal, due to neglect of capillary effects:

$$ \vec{w}_i = \frac{k_i}{\mu_i} \text{grad } p $$

(5)

where $k_0$ – absolute permeability of porous space; $k_i$ и $\mu_i$ – $i$-phase phase permeability and viscosity.

The curves of the functions of the relative phase permeability were taken in accordance with the experimental data obtained from a particular field.

The mathematical model includes the equation of internal energy for the mixture in general with the assumption of thermodynamic equilibrium of phases and considering the heat release in the decomposition reaction $Q$:

$$ \frac{\partial}{\partial t} \left( \sum_i \alpha_i \rho_i^o c_{vi} T \right) + \text{div} \left( \sum_i w_i \rho_i^o c_{vi} \text{grad } T \right) = \sum_i \text{div} (\lambda_i \text{grad } T) + Q $$

(6)

where $\alpha_i$ – $i$-phase volume concentration; $c_{vi}$ – $i$-phase heat capacity; $\lambda_i$ – $i$-phase thermal conductivity; $Q$ – heat introduced into the system during the phase transition.

According to the results of simulation, the mutual arrangement of zones saturated with various fluids was established. Initial conditions were set in accordance with reservoir conditions during well treatment after long-term operations. At the bottom hole zone a constant pressure or flow rate was set according to the injection conditions and usage of specific pumps.

As the results of numerical implementation of mathematical models for reservoir parameters listed in table 2 the pressure changes in the well, pressure fields in the bottom hole zone, water saturation fields, filtration rate fields, graphs of downhole pressure time changes and reagent injection rate were controlled. According to the results of phase saturation field changes, the thickness of the zones of active phases and washer was determined (Fig.1, a). It was assumed that the reaction retarder allows the injection of all fluids in the pumps operating mode.

Table 2. Parameters utilized while simulation.

| №   | Parameter                              | Unit Measure | Definition   |
|-----|----------------------------------------|--------------|-------------|
| 1   | Oil density, reservoir conditions       | tone/m$^3$   | 0.9628      |
| 2   | Oil viscosity before treatment          | mPa s        | 1100        |
| 3   | Oil viscosity, T=30 C                   | mPa s        | 770         |
| 4   | Oil viscosity, T=40 C                   | mPa s        | 283.5       |
| 5   | Oil viscosity, T=60 C                   | mPa s        | 66.7        |
| 6   | Permeability                            | mD           | 870         |
| 7   | Porosity                               | Decunit      | 0.3098      |
| 8   | Well radius                            | m            | 0.114       |
| 9   | Reservoir Thickness                     | m            | 24.8        |
| 10  | Current pressure in reservoir           | MPa          | 5.6         |
The next stage of calculations included the evaluation of the BM decomposition reaction development, during which heat and reaction products were released in the deposit and, accordingly, the temperature and pressure increased. At the present stage, the model was supplemented by the kinetics conditions of phase transitions (vaporization – condensation, sorption – desorption, decomposition of the solid phase of kerogen) typical for a particular deposit. The viscosity of the phases were defined depending on the temperature in accordance with experimental data. The concentration of chemically active substances did not affect the viscosity of the phases in the model. According to studies of the kinetics of the process [5] BM chemical decomposition reactions have the ability to self-acceleration, and their intensity increases strictly depending on BM solution at the beginning of the decomposition reaction. Based on that, the hydrodynamic model was assumed with pressure increasing gradually, reaching a maximum level of 120 atm an hour after reaction started (Fig.1, b). The obtained design pressures on the bottom hole featured a good matching comparing with the field pressure measurements data.

**Conclusion**

The experience of BM based TGCT field application in various fields of Russian Federation has shown greater efficiency of the method. Essential deposit changes led to inflow increase up from 3 to 7 times. The effect of EOR is registered as more longstanding (8-14 months). Also the inflow from the wells of idling well stock was obtained.

The use of BM has many advantages: the overall environmental safety, the relative cheapness of the components, the controllability of the process (with capacity to change the concentration of BM in water solution), non-waste process, the capacity to change the processing order in terms of individual parameters of field and even particular field. All this makes this method a priority for oil and gas fields in Russia. The results of numerical calculations of the process of BM impact on the deposit on the constructed complex model, considering the change in the structure of the pore volume and the phase composition of the saturating fluid, allow to run pretty accurate adaptation of the model to the history of production in the selected reservoir interval, correctly select wells-candidates and predict the effect of the treatment. Analysis of field experience data, among which about 10 % were unsuccessful, showed that the results of the TGCT method significantly depend on the specific (reservoir) conditions and bottom hole zone conditions, for example, such as destruction and clogging degree. The model allows not only to explain the results of successful as well as unsuccessful treatments, but to choose a
safe mode of TGCT application for other wells in the operating assets, preserving the operational capabilities of the wellbore.

The use of BM water solutions of higher concentrations and injected volumes may give a significant increase of temperature and pressure. And this, according to the authors of this work, may be favorable for the application of this method on kerogen deposits.

References
[1] Chazov G A, Azamatov V I, Yakimov S V, Savich A I 1986 Thermogaschemical treatment on marginal and complicated wells (Moscow: Nedra) p 153
[2] Alexandrov E N, Daragan E V, Domanov G P, etc. RF patent 2126084. Mode of access: http://allpatents.ru/patent/2126084.html
[3] Volpin S G, Smirnov N N, Kravchenko M N and Dieva N N 2014 Ecological Bulletin of Russia 3 17–21
[4] Volpin S G, Smirnov N N, Kravchenko M N, Kornaeva D A, Saidgareev A R and Dieva N N 2014 Oil industry 1 62–6
[5] Vershinin V E, Vershinina M V, Zavolzhsky V B, Gankin U A, Idiyatullin R A, Sosnin V A, Zimin A S and Lishchuk A N 2016 Oil industry 12 114–7
[6] Pestrikov A V, Basharov A R, Kravchenko M N 2009 Udnurt U. Bulletin. Math. Mech. Comp. S. 4 107–17
[7] Kravchenko M N, Dieva N N, Lishchuk A N, Muradov A V, Vershinin V E 2018 Georesources 20-3 178–83