Modeling and optimizing the design of matrix treatments in carbonate reservoirs with self-diverting acid systems

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Abstract. Application of a self-diverting-acid based on viscoelastic surfactant (SDVA) is a promising technology for improving the efficacy of acid treatment in oil and gas–bearing carbonate reservoirs. In this study, we present a mathematical model for assessing SDVA flow and reaction with carbonate rock using the SDVA rheological characteristics. The model calculates the technological parameters for acidizing operations and the prediction of well productivity after acid treatment, in addition to technical and economic optimization of the acidizing process by modeling different acid treatment options with varying volumes, injection rates, process fluids stages and initial economic scenarios.

Introduction

Acidizing carbonate reservoirs is the most common method for bottom-hole zone chemical treatments which are used to enhance oil recovery. Despite the years of experience and substantial volume of studies aimed at improving and enhancing efficiency of this method, a significant number of treatments do not provide positive results. One of the current problems in oil production is that acid treatments are not very efficient, particularly in the mature fields. This could be solved using materials that are capable of transformation and ensuring acid stimulation control [1-3]. Using such methods, more effective materials have been found that are capable of gelation and are resistant to acid.

An example of these improvements in acid viscosity management and diversion is an in-situ gelled acid. The main advantage of this, compared to the conventional acid stimulation, is the minimum number of steps necessary for acid diversion, since it allows simultaneous stimulation and diversion. The gelling material, based on viscoelastic surfactants, is injected and it clogs or reduces the permeability of stimulated reservoir zones. The gelling agent, injected after an acid solution, penetrates into the low permeability oil-saturated zone (as high-permeability zones are generally clogged with gel) reacts with the rocks, and forms new pore channels and expands existing ones. As a result, the permeability of low-permeability zones increases. Thus, self-diverting acid based on viscoelastic surfactant (SDVA) is seen as a promising approach to improving the efficacy of acid treatments. The self-diverting effect is based on the surfactant’s ability to form a viscoelastic gel during the acid reaction with carbonate rocks. The resulting gel creates an effective local diversion of new acid portions to untreated low-permeability zones. After the treatment, due to the susceptibility of cylindrical micelles to hydrocarbons, a deflecting gel is destroyed by oil and easily flows out of the
wellbore. Thus, the application of a self-diverting-acid based on viscoelastic surfactant provides an even treatment for the entire productive interval in oil reservoirs.

When designing acid treatments with diverters, it is essential to have justified calculations for agent injection rates, injected acid volumes, diverter volumes, the number of injection cycles, the number of diversion stages, and the volume of injected fluid at each stage to enable well performance prediction after treatment. It is also important to calculate the expected economic effect of well acidization. When designing large-scale selective acid treatments, the expected effects should be obtained from models of basic physical and chemical processes using dedicated software products [4]. For wells with a heterogeneous permeability profile, the problem of acid placement in target zones cannot be properly resolved without a numerical simulation. In addition, numerical simulations allow technical-economic optimization of well treatments by modeling scenarios with different volumes, stages of process fluids and initial economic cases.

SDVA rheological model
The rheological tests show that SDVA viscosity is described by a complex function of the spent acid concentration and the shear rate [5]. SDVA viscosity significantly increases with acid spending in a chemical reaction, which leads to flow diversion and, consequently, to more uniform wormhole propagation in carbonates. According to the results of rheological testing, the dependence of dynamic viscosity of the SDVA upon the acid concentration and shear rate [5]:

\[ \mu_a = K\dot{\gamma}^{(n-1)} \left[ 1 + \left( \frac{\mu_{\text{max}}}{\mu_0} - 1 \right) \exp \left( -\alpha \frac{(c - c_{\text{max}})^2}{c(1-c)} \right) \right] \]

(1)

where \( \mu_0 \) is the basic viscosity (viscosity at acid mass concentration \( c = 0.12 \) or 0), \( \mu_{\text{max}} \) corresponds to the maximum viscosity, defined relative to the reference value because of gelation, \( c_{\text{max}} \) is the acid concentration at maximum viscosity, and \( \alpha \) measures the acid concentration range for gel formation, which corresponds to the reciprocal variance (width) of the correlation between viscosity and acid concentration. With an \( \alpha \) value increase, the range of gelation decreases. In the above equation, \( K \) represents fluid consistency (Pa s). A higher viscosity corresponds to a higher consistency, \( \dot{\gamma} \) is the shear rate, s\(^{-1}\), \( n \) is an indicator of non-Newtonian fluid behaviour [6]. It is necessary to evaluate the following parameters of the model: \( K, n, c_{\text{max}}, \alpha. \)

The identification of model parameters is related to the solution of inverse problems that are ill-posed [7]. Additional assumptions can turn ill-posed problems into well-posed problems. The use of supplementary (a priori) information of a qualitative nature yields the Ivanov method of quasisolution [8]. In this case, as the inverse problem solution, the parameter set \( K, n, c_{\text{max}}, \alpha. \) gives a minimum of the residual function (equation 2) that can be considered as a correct solution for the described problem. The model was adjusted against the measured viscosity \( \mu^{\text{exp}} \) and calculated viscosity \( \mu^{\text{calc}} \) minimising the corresponding function

\[ J(K, n, c_{\text{max}}, \alpha) = \sum_i (\mu_i^{\text{exp}} - \mu_i^{\text{calc}})^2 \rightarrow \min. \]

(2)

The rheological model, describing the apparent SDVA viscosity behavior versus acid concentration and shear rate, is taken as a mathematical model for describing well acidizing with SDVA use in carbonate reservoirs [4]. The mathematical model optimizes well acidizing reactions using SDVA in
carbonate reservoirs and evaluates the effectiveness of acid treatment under specific reservoir conditions.

**Flow diversion efficiency**

Maintaining acid distribution over the whole producing interval is a major objective of acid treatments in carbonate oil and gas bearing reservoirs. Acid treatment modeling for various types of diverters showed that the diversion efficiency depends not only on properties of diverters, but on the heterogeneity in vertical permeability of stimulated reservoirs. Calculations show that if maximum well production increment is selected as an assessment criterion, an optimal treatment of high-permeability zones is the necessary condition. On the other hand, from the standpoint of effective reservoir depletion, the drainage of low-permeability layers with minimal impact on high-permeability ones is required. If the purpose of acid treatment optimization is efficient reservoir depletion, then, as a criterion of reservoir profile conformance after treatments, the design optimization algorithm takes square dispersion $D_q$, defined as the specific flow rate standard deviation from the average $Q_{av}$

$$
D_q = \frac{1}{n} \left[ \frac{Q_{av} - Q_i}{h_i} \right]^2 \left[ \frac{n^2 Q^2}{\sum_i h_i^2} \right] \right]^{-1}
$$

where $Q$ - total liquid rate, $n$ - number of layers, $Q_i$, $h_i$ - rate and thickness of $i$-th layer, respectively. In this case, minimum dispersion indicates a uniform zone treatment by hydrochloric acid. High dispersion points to an uneven reserve depletion or uneven sweep efficiency by waterflooding.

A promising alternative diversion technique is the application of materials capable of altering their properties (in particular, viscosity) directly during the process of acid treatment, thereby providing a certain control over the acidizing processes. An example of such an approach is acidizing with self-diverting acid that is based on viscoelastic surfactant (SDVA). Using the simulation, we compared the following different acid treatment designs for a layered-heterogeneous reservoir: the base case design without diverters (1), the design with viscous liquid application - INERA diverter (2) and a design with SDVA application (3). The total volume of working fluid in all cases corresponded to 36 m$^3$. When calculating designs (2) and (3) the volume of conventional acid composition was taken as 15 m$^3$. The volume of inhibited hydrochloric acid in design (1) corresponded to 30 m$^3$. Table 1 shows the distribution of initial permeability and porosity.

The dispersion, calculated for acidizing designs 1-3, is shown in Figures 1 and 2. Figure 1 shows the dispersion vs. agent injection rate while acidizing without diverters and with diverters INERA and SDVA (designs 1-3 of acidizing, respectively).

The calculations indicate that design (3), i.e. acidizing with SDVA, results in the smallest dispersion. When injecting the INER diverter at an initial rate of 0.1 m$^3$/min, the dispersion was the same as the design using SDVA. However, after some reduction, the dispersion flattens out later on. This can be explained by the nonlinear relationship between viscosity and injection rate. When the rate increases, the INER viscosity decreases and consequently the diverting properties calm down. When only inhibited acid is injected, the dispersion is higher than the one calculated in either design (3) with SDVA or design (2) with INERA. However, when the injection rate increases, the acid distribution over the interval for a zone increases and well dispersion decreases but remains higher than the dispersion when SDVA is used as a diverter.
Assessment of acidizing efficiency

Well performance after acid treatment is estimated using the Hawkins equation, which defines the equivalent formation damage skin factor $s$:

$$ s = k_0 \frac{r_{wh}}{r_w} \ln \frac{r_{wh}}{r_w} \int r k(r) \frac{dr}{rk(r)} $$

$k_0$ – untouched zone permeability around the wellbore, $k(r)$ – stimulated zone permeability around the wellbore, $r_w$ – wellbore radius, $r_{wh}$ – stimulated zone radius. For the selected designs we calculated the post-treatment skin values. Figure 2 shows skin values for low-permeability layers versus specific agent injection rate, used in the above mentioned designs. Specific agent consumption was calculated per a length unit of the layer thickness. Initial skin factor was 16. The calculations revealed that after well treatments with SDVA, skin of low-permeability layers decreased to negative values, while in designs (1) and (2), the post-treatment skin in low-permeability layers remained positive. The simulation results proved that SDVA application is highly efficient for acid treatments in carbonate reservoirs.

![Figure 1](image1.png)  
**Figure 1.** Well dispersion vs. agent injection rate  
1 - without diverters  
2 - INERA diverter  
3 - SDVA

![Figure 2](image2.png)  
**Figure 2.** Skin of low-permeability layer vs. injection specific volume  
1 - INERA diverter  
2 - without diverters  
3 - SDVA

Optimization steps

The optimization process is divided into several steps, corresponding to the selected measures. At each stage an optimal ratio between the volumes of acidizing stages and the diverter stages is determined. For each stage, an optimum injection rate is calculated, as well as cost effective volumes. The sequence of stages is fixed, however, one or more stages can be excluded from the overall sequence.
SDVA injection tests on cores have shown that acid treatment can be the most efficient process under certain optimal conditions [9]. Such conditions are described by an optimal Damköhler number. Under the optimal Damköhler number, several long dissolution channels (wormholes) can be created, penetrating into formations and providing the best connectivity between formation and wellbore. In the case of radial SDVA flow from the well into the formation, optimization ensures the optimum Damköhler number with regard to wormholes.

![Figure 3](image3.png)
**Figure 3.** Skin vs. SDVA injection rate at different acid injection rates $u$
1 - $u = 0.1 \text{ m}^3/\text{min}$; 2 - $u = 0.3 \text{ m}^3/\text{min}$
3 - $u = 0.5 \text{ m}^3/\text{min}$; 4 - $u = 0.7 \text{ m}^3/\text{min}$
5 - $u = 1 \text{ m}^3/\text{min}$

![Figure 4](image4.png)
**Figure 4.** Skin vs. SDVA volume at different acid injection volumes $V_a$
1 - $V_a = 1 \text{ m}^3$; 2 - $V_a = 5 \text{ m}^3$
3 - $V_a = 10 \text{ m}^3$; 4 - $V_a = 15 \text{ m}^3$
5 - $V_a = 20 \text{ m}^3$

To investigate the influence of SDVA injection rate and volume on the inflow profile conformance and acid treatment efficiency, the mathematical model was applied to the design cases for SDVA and inhibited acid injection. As Figure 3 shows, the skin changes versus the SDVA injection rates at different inhibited hydrochloric acid injection rates are non-monotone. The optimal range for the SDVA injection rate is from 0.25 $\text{ m}^3/\text{min}$ to 0.4 $\text{ m}^3/\text{min}$. The increase in the acid injection rate increases treatment efficiency.

Figure 4 shows the relationship between the skin and SDVA injection volumes at different acid injection volumes. The dynamic of the skin slows down with the increase in SDVA volume, and respectively decreases in conjunction with an increase in the injected acid volumes. Analysis of the results indicates that the optimum ratio of SDVA volume $V_{SDVA}$ to injected acid volume $V_a$ is related to the interval of $V_{SDVA} = (0.9 - 1.1)V_a$. The same values were obtained earlier [4] when calculating volumes of high viscosity liquid diverters. Analysis of previous well acidizing operations in carbonate reservoirs confirms that the unjustified increase in diverter volumes reduces the whole treatment efficiency.

**Conclusions**
A mathematical model can be used to effectively plan, design and optimize acidizing operations in carbonate reservoirs. In order to efficiently design acid treatment processes, an accurate simulation of complex acid dissolution and working fluid distribution in carbonate reservoirs is required.
Mathematical modeling also allows calculation of a preliminary injection program to achieve a negative skin, a number of hydrochloric acid injection cycles, a number of diversion stages using self-diverting acid systems, fluid injection volumes and rates at each stage.

This simulation experiment aimed to investigate the effect of SDVA injection rate and volume on injectivity profile conformance and acid treatment performance. The results revealed that combined use of SDVA and conventional acid composition reduces the injectivity profile non-conformance, compared to simple acid and nonlinear viscous liquids such as emulsions. In this case, the production increment has a nonlinear correlation with SDVA and acidic volumes, and their optimal volumes can be determined in the process of economic optimization. A criterion for determining the optimum ratio of SDVA and acid volumes was established, which ensures maximum inflow profile conformance under maximum acid treatment efficiency. The numerical studies revealed a need for simultaneous optimization on injection rates and volumes for both SDVA and consequent conventional HCl composition.

This study shows that mathematical modeling is useful for predicting the economic effects of acid treatments in carbonate reservoirs. Further use of these mathematical techniques in the future will make acidizing operations more efficient and reduce costs.

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