Influences of real-time acid-rock reaction heat on etched fracture dimensions during acid fracturing of carbonate reservoirs and field applications

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ABSTRACT

During acid fracturing, acid-rock reaction heat has a significant influence on temperature profiles in fractures and consequently on etched fracture dimensions. This can lead to misestimating of etched fracture dimensions. A model for calculating real-time acid-rock reaction enthalpy, which is a function of temperature, pressure and volumetric work of carbon dioxide produced by reactions, is coupled into a heat transfer model and a fracture growth model, and its effect on etched fracture dimensions is simulated. True experimental data from SL oilfield in China is used for simulation. The results show that acid-rock reaction heat reduces the effective etched fracture length by around 10%, and the effect of reaction heat on the etched fracture length in limestone is 10%–15% larger than in dolomite. Acid-rock reaction heat makes the etched width profile along a fracture more inhomogeneous. With consideration of acid-rock reaction heat, etched fracture widths are 15%–20% larger near the wellbore and over 20% narrower at fracture tip, and its effects are more intense in limestone than in dolomite. The influences of acid-rock reaction heat on etched fracture dimensions are stronger when the initial formation temperature is lower and when acid of high concentration is used. When the pump rate of acid fracturing is increased, the effect of acid-rock reaction heat on etched fracture dimensions is weakened. The new coupled models were used in carbonate reservoirs in Tarim Basin, China for acid fracturing optimization. A scenario comparison showed that the designed treatment parameters of acid fracturing should be different when acid-rock reaction heat was fully considered. The application of the optimized scenario resulted in at least three folds of production rate increase compared to that before stimulation.

1. Introduction

Carbonate reservoirs are extensively developed around the world. They account for about 70% of the global oil and gas resources [1]. Carbonates are characterized by strong heterogeneity and thus stimulations are usually needed to obtain good well productivity. Acid fracturing is the most commonly-used stimulation technology for carbonates, which creates fractures in the formation and etches fracture surfaces with acid, leaving conductive channels to provide flow paths for oil and gas [2, 3, 4]. Since the reaction of acid with carbonates is an exothermic reaction and the reaction kinetics is temperature-dependent, the acid-rock reaction heat plays a significant role in acid fracturing design and effectiveness evaluation.

Nevertheless, the research on acid fracturing in industry is mostly focused on acid-rock reaction modeling [5, 6, 7, 8, 9], hydraulic fracture propagation [10, 11, 12, 13], and acid leak off [14, 15, 16, 17]. The research on acid-rock reaction heat is rarely reported in the literature. Most of the acid-rock reaction study under different temperature
conditions ignored acid-rock reaction heat [18, 19, 20, 21], which may lead to deviation of the results from the truth. Lee and Roberts [22] considered acid-rock reaction heat as a boundary condition for a temperature profile model; Roodhart et al. [23] added an item describing acid-rock reaction heat to the energy conservation equation; Gu et al. [24] calculated the temperature increase caused by acid-rock reaction heat and added it to a temperature profile. Aljawad et al. [25] developed a fully integrated temperature model wherein acid-rock reaction heat was considered. However, they all took acid-rock reaction heat as a constant, ignoring its change caused by fluctuating temperature and pressure conditions in fractures. Actually, the pressure in a formation and fractures is not difficult to obtain [26, 27, 28, 29, 30], but the calculation of temperature is difficult because the acid-rock reaction enthalpy and temperature profiles in fractures have mutual effects on each other.

\[
\Delta \dot{Q}_a(T_w, p) = -13.692 + \frac{1}{1000} \left( -6.443 \times 10^{-3} T_w^2 + 16.075 T_w - \frac{17.406 \times 10^5}{T_w} \right) \\
+ \frac{1}{1000} f_{\text{fl}} \int_{1atm}^{p} \left[ V_{\text{CO}_2} - T_w \left( \frac{\partial V_{\text{CO}_2}}{\partial T} \right)_{p, T_w} \right] dp + \frac{1}{1000} p \cdot f_{\text{fl}} \cdot V_{\text{CO}_2}
\]

Guo et al. [31] took the acid-rock reaction heat as a varying parameter and incorporated it into a fracture temperature profile model for the first time in the petroleum industry. They investigated the influences of pressure, temperature as well as volume work of generated carbon dioxide on reaction enthalpy and the mutual effects of reaction heat and fracture temperature profiles. However, their research only focused on temperature changes in fractures. They did not evaluate the influences of the acid-rock reaction heat on etched fracture dimensions. In an acid fracturing design, the effective etched fracture length and width are the most direct indexes for evaluating the effectiveness of an acid fracturing scenario. Therefore, it is important to incorporate the acid-rock reaction heat calculation model into etched fracture dimension calculation models to optimize acid fracturing designs.

In this paper, a model for calculating real-time acid-rock reaction heat is coupled into a heat transfer model and a fracture growth model, based on which a method of calculating an acid etched fracture length and width is developed. The effects of acid-rock reaction heat on etched fracture dimensions are then simulated using true experimental data and their significant understandings are obtained. The objective of this study is to explore the impacts of acid-rock reaction heat on acid fracturing effectiveness so as to give suggestions on acid fracturing design optimization in carbonate reservoirs.

2. Models establishment

This section mainly describes the models of calculating acid-rock reaction heat, the heat transfer in fractures and the etched fracture dimensions and how we coupled these models to investigate the influence of acid-rock reaction heat.

2.1. Model of acid-rock reaction heat

Guo et al. [31] derived the expression of molar reaction heat of hydrochloric acid and limestone with considerations of temperature, pressure and the volumetric work done by carbon dioxide, which is

\[
\Delta_{\text{m}} Q_a(T_w, p) = -43.272 + \frac{1}{1000} \left( -21.508 \times 10^{-3} T_w^2 + 49.552 T_w - \frac{1.46 \times 10^5}{T_w} \right) \\
+ \frac{1}{1000} 2f_{\text{fl}} \int_{1atm}^{p} \left[ V_{\text{CO}_2} - T_w \left( \frac{\partial V_{\text{CO}_2}}{\partial T} \right)_{p, T_w} \right] dp + \frac{1}{1000} 2p \cdot f_{\text{fl}} \cdot V_{\text{CO}_2}
\]

The expression of acid-dolomite reaction heat is a little different from that of limestone, which is because their reactants and resultants are different (Eq. (3)) and the values of thermodynamic parameters are, therefore, different. Besides, two moles of carbon dioxide instead of one are generated by reaction of one mole of dolomite:

\[
\text{CaMg(CO}_3\text{)}_2 + 4\text{H}^+ \rightarrow \text{Ca}^{2+} + \text{Mg}^{2+} + 2\text{H}_2\text{O} + 2\text{CO}_2 \uparrow
\]

Eqs. (1) and (2) can be used to investigate the influences of temperature, pressure and the volumetric work on the molar reaction heat for limestone and dolomite, respectively.

2.2. Model of heat transfer in fractures

In a real acid fracturing treatment, the acid-rock reaction heat influences the temperature distribution along fractures and temperature in the fractures, in turn, impacts the acid-rock reaction rate. In order to fully consider these mutual interactions, the above model must be coupled into a heat transfer model in fractures. Guo et al. [31] have used a two-dimensional heat transfer model to describe these interactions, which is

\[
\frac{\partial (\rho C_f T)}{\partial x} + \frac{\partial (\rho C_f T)}{\partial y} = -\frac{K_f}{\rho C_f} \frac{\partial^2 T}{\partial y^2}
\]

with boundary conditions...
\[ x = 0, \quad T = T_0 \] (5)

\[ y = 0, \quad \frac{\partial T}{\partial y} = 0 \] (6)

and

\[ y = \pm \frac{w}{2} K_s \frac{\partial T}{\partial y} = k_s C^m \left[ -\Delta Q_m(T_w, p) \right] + q_0(t) \] (7)

where \( \Delta Q_m(T_w, p) \) is the acid-rock reaction heat, which has been expressed by Eqs. (1) and (2). \( C^m \) is the acid concentration with the order of the reaction and \( m \) can be computed from the mass transfer model. Numerical solutions were obtained from Eqs. (4), (5), (6), and (7) and the impacts of acid-rock reaction heat on fracture temperature profiles were studied by Guo et al. [31]. The same model is then used to calculate etched fracture dimensions.

2.3. Model of etched fracture dimensions

A temperature change in fractures consequently influences the etched fracture length and width and ultimately influences the acid fracturing effectiveness. The PKN (Perkins-Kern-Nordgren) fracture propagation model is selected [32], and hence the effective acid penetration distance (or effective etched fracture length) and the etched fracture width are calculated.

2.3.1. Calculations of effective acid penetration distance

During acid fracturing, as the acid flows along fractures to the deep formation and it reacts with rocks while flowing, the acid concentration gradually decreases. When the acid concentration is reduced to a certain level (usually 10% of the initial concentration of the acid), the acid loses its reactive ability and becomes spent acid. The distance that the acid travels before it becomes spent acid is called the effective penetration distance of reactive ability and becomes spent acid. The distance that the acid travels before it becomes spent acid is called the effective penetration distance of reactive ability and becomes spent acid. The effective acid penetration distance can be obtained by superposition of the etched fracture width at each time step during the whole treatment. In fact, after pumping stops, the reaction rate and the reaction time of acid and rock vary along a fracture, the etched fracture width in each fracture element is different as well. Taking the stimulation of limestone as an example, the acid-rock reaction rate within a fracture element is \( k_s C^m \). Then, the amount of HCl participating in the reaction during \( \Delta t \) in this element is \( 2k_s C^m \Delta x \Delta t \), and the volume of the dissolved rock during this time period can be calculated from expression (14):

\[
\frac{100k_s C^m \Delta x \Delta t}{(1 - \varphi)\rho_{CaCO_3}}
\]

(14)

By the law of volume conservation, the change in the etched fracture volume equals the materials that have been dissolved by acid can be calculated by Eq. (15):

\[
[w_r(t + \Delta t) - w_r(t)]h \Delta x = \frac{100k_s C^m \Delta x \Delta t}{(1 - \varphi)\rho_{CaCO_3}}
\]

(15)

The change in the etched fracture width during \( \Delta t \) is then calculated by Eq. (16):

\[
\Delta w_r = [w_r(t + \Delta t) - w_r(t)] h = \frac{100k_s C^m \Delta t}{(1 - \varphi)\rho_{CaCO_3}}
\]

(16)

Similarly, the change in the etched fracture width for dolomite can also be calculated by Eq. (17):

\[
\Delta w_r = [w_r(t + \Delta t) - w_r(t)] h = \frac{92k_s C^m \Delta t}{(1 - \varphi)\rho_{dolomite}}
\]

(17)

The total etched width in a fracture element at the time of pump stop can be obtained by superposition of the etched fracture width at each time step during the whole treatment. In fact, after pumping stops, the acid-rock reaction will continue, and the width of the etched fracture will still increase. Besides, the etched fracture width may be eroded by the closing pressure after the fracture closes. We do not consider these factors here since we are focusing on the influence of acid-rock reaction heat on the dimensions of the acid etched fracture.

3. Influence analysis

3.1. Influences of acid-rock reaction heat on effective acid penetration distance

The effects of acid-rock reaction heat on the effective acid penetration distance are studied considering the variances of rock types, acid concentrations, formation temperatures and pumping rates. The input
parameters for calculations are the true experimental data from SL oilfield in China. The results are shown in Tables 1, 2, 3, and 4.

The results from Tables 1, 2, 3, and 4 lead to understandings as follows:

First of all, with consideration of acid-rock reaction heat, the effective acid penetration distance is reduced by about 10%, which is because the temperature in the fracture is increased by the acid-rock reaction heat and it accelerates the reaction speed of acid and rock, which further leads to rapid consumption of acid.

Secondly, under the same reaction conditions, the effective acid penetration distance in dolomite is longer than that in limestone, and the effect of acid-rock reaction heat on the effective acid penetration distance in limestone is larger than that in dolomite by 10%–15%; this is because the heat generated by the reaction of limestone and acid is more since the reaction is faster.

Besides, a higher acid concentration and a lower original formation temperature result in a longer effective acid penetration distance and a bigger effect of acid-rock reaction heat on the effective acid penetration distance. This is because a high acid concentration accelerates the reaction rate and consequently fastens the generation of reaction heat; when the initial formation temperature is low, the contribution of reaction heat to the fracture temperature is more significant.

A larger pumping rate also leads to a longer effective acid penetration distance but a smaller effect of acid rock reaction heat. This is because a large pumping rate makes acid travel faster in fractures and thus arrive at a farther distance before it becomes spent acid. Simultaneously, it reduces the reaction time by decreasing the treatment time and thus weakens the effect of reaction heat.

These understandings are important for acid fracturing design and effectiveness evaluation.

### 3.2. Influences of acid-rock reaction heat on etched fracture width

Figures 1 and 2 show the distributions of the etched fracture width along the hydraulic fracture length before and after considering the acid-rock reaction heat. It can be seen obviously that the acid-rock reaction heat has a significant influence on the etched width: with consideration of reaction heat, the etched width near the wellbore is larger, while the etched width far away from the wellbore becomes smaller. In short, acid-rock reaction makes the etched width distribution more “concentrated” (here means that most of the etched width gathers at a specific interval, which makes etched width distribution uneven) near the wellbore.

The above “concentration” effect is unfavorable to acid fracturing, because it causes even more non-uniform etched width distribution along the fracture and is disadvantageous for improving the fracture conductivity after acid fracturing.

To better illustrate the influences of acid-rock reaction heat, the differences of the etched fracture width distributions caused by reaction heat for different rock types, different acid concentrations, different formation temperatures and different pumping rates are calculated and shown in Figures 3, 5, 7, and 9, respectively. Besides, the impact degree, which is defined as the ratio of the etched width change caused by reaction heat to the etched width with no consideration of reaction heat, is also calculated and shown in Figures 4, 6, 8, and 10. The impact degree can directly show the effect extent of acid-rock reaction heat on the etched fracture width distribution.

| Item          | Well A       | Well B       |
|---------------|--------------|--------------|
| Rock type     | limestone dolomite limestone dolomite |
| Considering reaction heat | 0.405 0.492 0.582 0.661 |
| Ignoring reaction heat | 0.439 0.530 0.642 0.722 |
| Effect        | 8.22% 7.52% 10.38% 9.13% |

As we can see from Figures 3 and 4, the absolute value of the change in the etched fracture width and the impact degree of acid-rock reaction heat on the etched fracture width in limestone are both significantly bigger than those in dolomite. Under the simulation conditions in the study, the acid-rock reaction heat increases the etched fracture width by 0.13 cm at maximum for limestone, while the value is only 0.08 cm for dolomite. For both limestone and dolomite, the biggest impact degree is positive 15%–20% near the wellbore and becomes negative (−20%) after 0.3–0.4 of the dimensionless distance from the wellbore, where positive means an increase and negative means a decrease. This indicates
that the acid-rock reaction heat makes the etched width distribution more “concentrated” to the near-wellbore area, which is unfavorable for creating a long-etched fracture.

Figures 5 and 6 show that with an increase in acid concentration, the reaction heat increases the etched fracture width near the wellbore more but decreases the etched width in the far-wellbore area more; i.e., the “concentration” effect becomes more serious. Therefore, measures should be taken to counteract the negative effects of acid-rock reaction heat, especially when acid of high concentration is used. These measures include increasing the amount of pre-pad fluid to fully cool the formation, adding a thickening agent to the acid to reduce the reaction rate, and improving the pumping rate to shorten the reaction time.

Figures 7 and 8 show that the initial formation temperature has a very small influence on the change in the etched fracture width as well as the impact degree. The “concentration” effect is slightly higher when the formation temperature is higher. This indicates that the influence of the initial formation temperature on the etched fracture width can be ignored.
Obtain a more uniform etched fracture width distribution. Therefore, the pump rate during acid fracturing should be increased to reduce the effect of acid-rock reaction heat on the etched fracture width distribution to some extent. This indicates that a high pump rate can reduce the impact degree of reaction heat, and the smaller the negative its influence is. We can see that the higher the pump rate, the greater the positive influence of reaction heat, and the smaller the negative influence. Moreover, the positive impact degree of reaction heat is larger at a higher pump rate. Figure 8 shows the impact degree of reaction heat on the etched fracture width-different formation temperatures. Figure 9 shows the difference of etched fracture width before and after considering reaction heat-different pump rates. Figure 10 shows the impact degree of reaction heat on the etched fracture width-different pump rates.

Figures 9 and 10 show comparisons of the etched fracture width change due to the acid-rock reaction heat at different pump rates. We can see that the higher the pump rate, the greater the positive influence of reaction heat, and the smaller the negative influence. Moreover, the positive impact degree of reaction heat is larger at a higher pump rate. This indicates that a high pump rate can reduce the effect of acid-rock reaction heat on the etched fracture width distribution to some extent. Therefore, the pump rate during acid fracturing should be increased to obtain a more uniform etched fracture width distribution.

4. Field applications

A simulator is developed based on the above coupled models and can be used for predicting the etched fracture dimensions during acid fracturing with consideration of the acid-rock reaction heat. Therefore, it can be used to optimize an acid fracturing program by taking the following steps: firstly, collect the basic data required for simulation, including geological data, physical and chemical parameters of rock, formation temperature and pressure data, and physical and chemical properties of acid and the designed stimulation parameters; then, input the data into the simulator and compute the etched fracture dimensions, including the effective acid penetration distance and the etched fracture width profile; afterwards, check if the etched fracture dimensions meet our requirement; if not, adjust the designed stimulation parameters and run the simulator again until the results are satisfied.

We introduce a case of field application of our method in a true well. Well JY8 is located in Tarim Basin, western China. The pay zone of this well is Ordovician. The buried depth is 7190 m. The lithology is gray micritic limestone, in which the calcium carbonate content is 92–98%. The initial formation temperature is 160 °C. The formation pressure coefficient is 1.12. The natural oil production rate of the well is only 15.6 m³ per day, which is far lower than its allocated production. Acid fracturing is determined to be used to enhance the productivity. Initially, 28% HCl was considered. However, based on our simulation results, the effective acid penetration distance (namely the effective etched fracture length) was only 58.6 m with a pumping rate of 5 m³/min and acid volume of 160 m³ in total. Due to quick consumption of the acid, the width of the etched fracture was 1.9 cm near the wellbore and quickly decreased to almost zero at 50 m from this wellbore.

Obviously, a near-wellbore area was over-etched while the far-wellbore area was under-stimulation. This not only brought about risks of wellbore collapse and solid production, but also restricted the fracture conductivity at the far-wellbore end. To avoid these problems, three measures were then taken to optimize the acid fracturing scenario. First of all, we reduced the acid concentration to 20%. Secondly, we added a gelling agent to the acid formula to increase its viscosity to 38 mPa.s to slow down the acid-rock reaction rate. Finally, we used a large volume of pre-pad fluid, 200 m³ of guar gum fracturing fluid (account for 56% of the total fluid volume), to fully cool the formation before pumping in the acid.

The optimized stimulation fluid was as follows: 200 m³ pre-pad fluid +160 m³ HCl with concentration of 20% + 0.8% gelling agent + other additives. The simulation results under a pumping rate of 5 m³/min were shown in Figure 11. It is shown that the etched fracture width near the wellbore was reduced by about 30%, which greatly reduced the risk of wellbore collapse. The effective acid penetration distance was increased to 88.9 m, which greatly improved the effective etched fracture length and consequently the stimulation effectiveness.

The well produced 98.5 m³ oil per day after acid fracturing with the optimized stimulation scenario, which was 6.3 times the initial production rate.

Beside this well, the simulator and the method have been used in another four carbonate wells in the same block in Tarim Basin for optimizing the acid fracturing design. The production rates of these four wells were improved by more than three times on average compared to the production data before stimulation. This indicates that taking the acid-rock reaction heat into consideration is very significant in acid fracturing design.

5. Discussion

In this paper, a model of calculating acid-rock reaction heat was coupled into a heat transfer model in fractures and a fracture growth model. The effect of acid-rock reaction heat on acid etched fracture dimensions was studied. However, more considerations can be added to our models to make them better.
6. Conclusions

In this study, a model for calculating real-time acid-rock reaction enthalpy is coupled into a heat transfer model and a fracture growth model, and a simulator of calculating the etched fracture dimensions with full consideration of acid-rock reaction heat is developed. The following conclusions can be drawn based on our study:

(1) A model for calculating real-time acid-rock reaction enthalpy, which is a function of temperature, pressure and volumetric work of carbon dioxide produced by reaction, must be coupled into a heat transfer model and a fracture growth model to predict the etched fracture dimensions.

(2) Acid-rock reaction heat reduces the effective etched fracture length, and the effect of reaction heat on the etched fracture length in limestone is larger than that in dolomite.

(3) Acid-rock reaction heat makes the etched width profile along the fracture more inhomogeneous. With consideration of acid-rock reaction heat, etched fracture widths are larger near the wellbore and narrower at the fracture tip, and these effects are more intense in limestone than that in dolomite.

(4) The influences of acid-rock reaction heat on etched fracture dimensions are stronger when the initial formation temperature is lower and an acid of high concentration is used. But the influence of the initial formation temperature on the etched fracture width is very small and can be neglected.

(5) When a pumping rate in acid fracturing is increased, the influence of acid-rock reaction heat on etched fracture dimensions is weakened. Increasing the pumping rate is an effective method to reduce the negative influence of acid-rock reaction heat.

(6) The general effect of the acid-rock reaction heat is that it makes the etched fracture width distribution more "concentrated", which is unfavorable for reservoir stimulation. Enhancing the pumping rate, using a pre-pad fluid to cool the formation and using acid with relative low concentration can reduce the negative effect of the reaction heat to some extent.

(7) The new coupled model is used for acid fracturing optimization in five carbonate wells in Tarim Basin, China. The optimized acid fracturing scenarios resulted in at least three folds of production rate increase compared to the production rate before stimulation.

Declarations

Author contribution statement

Huifeng Liu: Conceived and designed the experiments; Wrote the paper.
Babedaer Baletabieke, Gang Wang: Performed the experiments.
Jianchun Guo: Analyzed and interpreted the data.
Fuguo Xia: Contributed reagents, materials, analysis tools or data.
Zhangxin Chen: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Conflict of interest

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] Jianchun Guo, Bo Gou, Nan Qin, Junsheng Zhao, Lin Wu, Kunjie Wang, Jichuang Ren, An innovative concept on deep carbonate reservoir stimulation: three-dimensional acid fracturing technology, Nat. Gas Ind. Phase 2 (2020). ORCID: 0000-0001-9601-1203.

[2] J. Guo, B. Gou, N. Qin, J. Zhao, L. Wu, K. Wang, J. Ren, An innovative concept on deep carbonate reservoir stimulation: three-dimensional acid fracturing technology, Nat. Gas. Ind. B 7 (5) (2020) 484–497.

[3] J. Guo, L. Zhan, B. Gou, R. Zhang, C. Liu, X. Li, J. Ren, Formation of fractures in carbonate rocks by pad acid fracturing with different states of carbon dioxide, Petrol. Explor. Dev. 48 (3) (2021) 744–751.
[4] B. Gou, C. Guan, X. Li, J. Ren, J. Zeng, L. Wu, J. Guo, Acid-etching fracture morphology and conductivity for alternate stages of self-generating acid and gelled acid during acid-fracturing, J. Petrol. Sci. Eng. 200 (2021) 108358.

[5] J. Romeroe, H. Gu, S.N. Gulrajani, 3D transport in acid-fracturing treatments: theoretical development and consequences for acid hydrocarbon production, SPE Prod. Facil. 16 (2) (2001) 122–130.

[6] Y.M. Li, J.C. Guo, J.Z. Zhao, H. Liu, J.F. Yu, J.Y. Liu, Study on numerical computation model of 3-D flow and reaction of acid, J. Southwest Pet. Inst. 23 (5) (2001) 42–45 (in Chinese).

[7] G.Y. Jiao, L.Q. Zhao, P.L. Liu, P.T. Pei, Application of fully 3-D reaction model of acidizing fluid in acid fracturing, Nat. Gas. Ind. 26 (4) (2006) 62–64 (in Chinese).

[8] I.A. Volnov, R.D. Kanevskaya, Modeling of acid treatment in oil reservoirs, in: Paper SPE 138051, presented at the SPE Russian Oil and Gas Conference and Exhibition, Moscow, Russia, 2010, pp. 26–28.

[9] Pournik-M., Li, Li, Smith,B., Naar-EI-Din, H.A: Effect of acid spending on etching and acid fracture conductivity. Paper SPE 136217, presented at the SPE Russian Oil and Gas Conference and Exhibition, Moscow, Russia., 26-28.

[10] P. Zhang, J.Z. Zhao, D.L. Guo, Study on numerical simulation of 3-D propagation of hydraulic fractures, Oil Drill. Prod. Technol. 19 (3) (1997) 53–59 (in Chinese).

[11] L.J. Ji, D.L. Guo, J.Z. Zhao, G. Wu, 3-D models and its computation of acid fracture simulation, Drill. Prod. Technol. 23 (1) (2000) 39–43 (in Chinese).

[12] D.L. Guo, L.J. Ji, J.Z. Zhao, C.Q. Liu, 3-D fracture propagation simulation and production prediction in coalbed, Appl. Math. Mech. 22 (4) (2001) 337–344.

[13] Y.M. Li, J.Z. Zhao, J.C. Guo, Numerical simulation of 3-D fracture propagation with vertical pressure gradient, Drill. Prod. Technol. 24 (1) (2001) 34–37 (in Chinese).

[14] A.D. Hill, D. Zhu, Y.M. Wang, The effect of wormholing on the fluid loss coefficient in acid fracturing, SPE Prod. Facil. 10 (4) (1995) 257–264.

[15] Y.M. Li, J.C. Guo, J.Z. Zhao, X.L. Liu, Study on acid leak-off in naturally fractured reservoirs, J. Southwest Pet. Inst. 26 (2) (2004) 50–53 (in Chinese).

[16] C.G. Chen, J.C. Guo, J.Z. Zhao, Novel calculation method of acid leak-off considering the effect of acid wormhole, Oil Drill. Prod. Technol. 27 (6) (2005) 79–84 (in Chinese).

[17] J.C. Guo, T.C. Li, J.Z. Zhao, Study on calculation procedures of the acid filtration controlled by the wormhole in the acid fracturing, Drill. Prod. Technol. 29 (5) (2006) 35–38 (in Chinese).

[18] B. Gou, C. Guan, X. Li, J. Ren, J. Zeng, L. Wu, J. Guo, Acid-etching fracture morphology and conductivity for alternate stages of self-generating acid and gelled acid during acid-fracturing, J. Petrol. Sci. Eng. 200 (2021) 108358.

[19] J. Du, G. Guo, P. Liu, G. Xiong, F. Xu, A novel method for fracture pressure prediction in shallow formation during deep-water drilling, J. Energy Resour. Technol. (2021) 1–35.

[20] J. Yang, S. Liu, L. Shi, J. Zhou, X. Yang, Research on prediction model for formation pressure in compression structure, Acta Petrol. Sin. 30 (5) (2009) 764–768.

[21] F. Zeng, X. Cheng, J. Guo, Z. Chen, J. Xiang, Investigation of the initiation pressure and fracture geometry of fractured deviated wells, J. Petrol. Sci. Eng. 165 (2018) 412–427.

[22] F. Zeng, F. Peng, B. Zeng, J. Guo, S. Pari, S. Zhang, Z. Chen, Perforation orientation optimization to reduce the fracture initiation pressure of a deviated cased hole, J. Petrol. Sci. Eng. 177 (2019) 829–840.

[23] Jianchun Guo, Huifeng Liu, Yuexuan Liu, Effects of acid-rock reaction heat on fluid temperature profile in fracture during acid fracturing in carbonate reservoirs, J. Petrol. Sci. Eng. 122 (2014) 31–37.

[24] R.P. Nordgren, Propagation Of A Vertical hydraulic fracture, SPE J. 12 (4) (1972) 306–314.

[25] Y. Peng, J. Zhao, K. Sepehrnoori, Y. Li, W. Yu, J. Zeng, Study of the heat transfer in the wellbore during acid/hydraulic fracturing using a semianalytical transient model, SPE J. 24 (2) (2019) 877–890.

[26] A. Al-Momin, D. Zhu, A.D. Hill, The Effects of Initial Condition of Fracture Surfaces, Acid Spending and Acid Type on Conductivity of Acid Fracture, OnePetro, 2014.

[27] Y. Gao, S. Lian, Y. Shi, X. Yang, F. Zhou, C. Xiong, F. Li, X. Han, N. Zhang, A New Acid Fracturing Fluid System for High Temperature Deep Well Carbonate Reservoir, OnePetro, 2016.

[28] Successful Implementation of Multi-Modal, Self-Assembling, Self-Degradable and Environmentally Friendly Solids Particulates as Diverter in Acid Stimulation Treatments in Carbonate Reservoirs | SPE/IADC Middle East Drilling Technology Conference and Exhibition/OnePetro, in: https://onepetro.org/SPEMEDT/proceedings-abstract/18MEDT/3-18MEDT/D0315017 R004/214765 (accessed 2022-10-25).

[29] A. Lutfullin, R. Khassimov, I. Manurov, K. Ovchinnikov, E. Malayevko, Conducting Multi-Stage Acid Hydraulic Fracturing in Carbonate Formations with Subsequent Intervals Production Efficiency Monitoring, OnePetro, 2019.