Research and Application of the Composite Reservoir Stimulation Technology for Ultra-High-Temperature Ultra-Deep Naturally-Fractured Carbonate Reservoirs

Guifu Duan1,2,*, Chunming He1, Chong Liang1, Bo Cai1, Jun Yan1 and Chao Wang1

1Research Institute of Petroleum Exploration & Development, PetroChina, Beijing, 100083, China
2China University of Petroleum, Beijing, 102249, China

*Corresponding author email: duanguifu@petrochina.com.cn

Abstract. The Ordovician buried-hill carbonate reservoir in the northern Jizhong Sag of China is seen with abundance in hydrocarbon resources. Nonetheless, attempts of multiple reservoir stimulation technologies have all failed to make breakthrough, due to its lithological complexity (mixture of dolomite and limestone), ultra-high temperatures (180°C) and high in-situ stress gradients (0.023 MPa/m), Given the aforementioned reservoir geological challenges, reservoir evaluation, technology optimization and plan design starting from the reservoir geological characteristics have been carried out, and the “composite” reservoir stimulation technology for ultra-high-temperature ultra-deep naturally-fractured carbonate reservoirs has been proposed. In terms of the short effective affected distance of acid under high temperatures (180°C), low conductivity sustainability owing to high closure stresses (induced by the burial depth of 5,000 m), extreme difficulties in expanding stimulated reservoir volumes (large lateral in-situ stress differences and long vertical spans), the practice of “multi-stage injection, temporary plugging and diversion, and propped acid fracturing” highlighting high pump rates and combination of low- and high- viscosity fluids (acid and fracturing fluids) has been developed and evolves into the network fracturing technology capable of inter-layer temporary isolation and within-layer diversion. The above technology has been applied in Well AT1x, with high volumes of fluid consumption and the maximum pump rate of 11 m³/min. Safe and efficient operation over six hours featuring challenges such as 3,000 m³ of composite fluids, ultra-high temperatures and ultra-high pressures is achieved. On-site monitoring such as the micro-seismic monitoring and simulation results show that compared with the previous reservoir stimulation, the developed technology presents SRV 3.5 times larger, and results in three-dimensional reservoir reconstruction. The post-fracturing daily gas production amounts to 409,000 m³ and daily oil production, 71 m³. In production testing, the wellhead pressure maintained over 25 MPa, and the daily gas production exceeds 100,000 m³, which indicate stable pressures and production, and a safe wellbore. The application accomplishes the design goal of integrated exploration and exploitation, and geology and engineering, and provides references for reservoir simulation of analogous reservoirs.

Keywords: Ultra-high temperature; Ultra-deep; Composite reservoir stimulation; Carboxymethyl fracturing fluid; Temporary plugging and diversion.

1. Introduction
Over recent years, deep high-temperature oil and gas reservoirs have become an important frontier for energy source replacement, as targets of oil and gas exploration are increasingly complex [1]. The
buried hill structures in the northern Jizhong Sag, such as the Yangshuiwu buried hill, possess hydrocarbon in place over one hundred million tons, and are considered as an emerging field for oil and gas resource replacement in the Bohai Bay area [2, 3]. Exploration in this sag starts in 1980s, during which Wells WG1, WG2 and WG4 are drilled successively and all present certain hydrocarbon show [4]. Given the reservoir characteristics and requirements of reservoir stimulation techniques, the small-scale propped fracturing, acid fracturing using gelled acid and composite acid fracturing practice of propped fracturing and clean acid fracturing are applied one after another. However, the effective stimulated time is limited, no stable production occurs, the stimulation result is unsatisfactory and no exploration breakthrough has been achieved, although production is to some extent stimulated. Over the past few years, constant progress is seen in the reservoir stimulation technique for deep reservoirs [5,6]. Ultra-high-temperature, ultra-deep reservoir stimulation technologies are found with breakthrough in Bakken, Eagle Ford, etc., of North America and also in the Tarim Basin and Sichuan Basin of China, which provides new inspiration for reservoir stimulation in this area [7]. Nonetheless, compared with reservoirs of marine facies in the Tarim Basin and Sichuan Basin in China, the carbonate reservoir of the study area is facing more challenges, such as the more complex lithology (interbedding of dolomite and limestone), higher temperatures (180ºC), higher in-situ stress gradients (0.023 MPa/m), fast acid-rock reaction and limited stimulated distance. Reservoir stimulation techniques specific to the characteristics of the study area are in demand.

This paper, on the basis of experience of reservoir stimulation in analogous reservoirs both in China and other countries and also inspiration from reservoir reconstruction practice in the study area, adopts the fracturing fluid materials and acid system rated for 180ºC, and develops the composite temporary-plugging technique using fibres + diverting acid + proppant that is able to improve the affected distance of acid fracturing and achieve within-layer diversion and inter-layer temporary plugging and “soft” layer separation. Moreover, the support technique for safe implementation of high-pump-rate, high-fluid-volume, multi-fluid alternate injection has taken shape. In field applications of the aforementioned techniques, Well AT1x presents high-rate oil and gas streams with post-fracturing daily oil production of 71 m3 and daily gas production of 400,000 m3, which shall provide advanced technical guidance upon high-efficiency stimulation of ultra-high-temperature ultra-deep complex reservoirs in China.

2. Reservoir Geological Features and Challenges for Stimulation

2.1. Overview of Geological Features

The previous drilling and exploration of the condensate gas reservoir in northern Jizhong area demonstrate that the reservoir features low permeability (0.1×10⁻³–0.3×10⁻³ μm²), low porosity (5%–8%), natural fractures dominated by micro and fine cracks that are highly filled and thus have inferior connectivity, high in-situ stress gradients (0.023 MPa) and large differences between the maximum and minimum horizontal stresses (7–10 MPa). With respect to such reservoir features, attempts of multiple reservoir stimulation techniques have been made, including propped fracturing, large-scale acid fracturing using gelled acid, repeated fracturing, large-scale acid fracturing using clean acid, etc. The resultant fracture is mainly single, with half length of only 80–120 m and limited connected distance, leading to failure to fulfill the purpose of deep-penetration reservoir stimulation by complex fractures. The reservoir simulation treatment turns out to provide short effective time and no stable production, and such results are unsatisfactory, although production stimulation is to some extent realized. A set of new reservoir simulation technique and practice applicable to the intrinsic reservoir geological features and technical difficulties of this block are demanded, for breakthrough in the new frontier of condensate gas reservoirs in the northern Jizhong Sag. Considering the reservoir geological features presented above, the reservoir stimulation difficulties are summarized as follows:

1. The reservoir lithology is characterized by interbedding of limestone and dolomite. Acid-rock reaction in dolomite is simpler in terms of the process, and the reaction rate is higher than that of dolomite reservoirs under the reservoir condition. However, the effective stimulated distance of acid shortens, as acid-rock reaction accelerates.

2. The reservoir, which is tight and deep buried, is seen with high breakdown pressures. Hence, it is
difficult to create and maintain effective fractures in the formation. The operation pressures during fracturing have reached over 80 MPa in multiple previous wells, and the fracture closure pressure exceeds 100 MPa. The pump rate in operation is limited, and it is found barely possible to fulfill the requirements of SRV-oriented reservoir simulation (SRV = Stimulated Reservoir Volume).

(3) The reservoir has a large vertical span (> 100 m), and thus effective selective fracturing and sufficient utilization of layers are extremely challenged.

(4) The burial depth of the reservoir is 5,000 m, accompanied by the formation temperature up to 180°C. This requires higher performances of fracturing fluids in terms of thermal and shearing resistance and of acid solutions regarding corrosion inhibition and reaction retardation.

(5) The closure pressure of the reservoir exceeds 80 MPa, and thus fracture conductivity is hard to maintain.

In reference to the aforementioned difficulties, integrated research on reservoir stimulation that incorporates the geological features needs to be carried out, in order to confirm geological factors affecting network fracturing, explore the networking fracturing technique capable of within-layer fluid diversion and inter-layer temporary plugging and its material system, and develop corresponding technical approaches for post-fracturing management and monitoring, which ultimately achieves systematic integration of geology and engineering, and exploration and exploitation.

3. Research on the Composite SRV-oriented Reservoir Simulation Technique

3.1. Enhancing Conductivity of Complex Fractures under High Closure Pressures

3.1.1. Acid Etching Characteristics under High Closure Pressures. Studies of both China and other countries have demonstrated that irregular etching of acid on fracture surfaces is mainly related to the reservoir lithology and heterogeneity and also injection process. The deep Ordovician buried-hill carbonate reservoir has strong heterogeneity in minerals, and thus fracture acid etching is seen with high irregularity, leading to high conductivity of etched fractures (Figure 1). In terms of the injection process, the “preferential flow channel” left after primary etching of acid can be further dissolved, by increasing the quantity of acid injection stages. As a result, the fracture width is expanded, fracture conductivity of multi-stage injection is higher than that of single-stage injection by 25%, and more importantly, the fracture conductivity maintained of multi-stage injection is increased by 40%. On the basis of the comprehensive analysis, it is believed that alternative injection involving 2–4 stages is suitable for acid fracturing in this block.

![Etching the fracture entrance](image1)
![Etching the fracture tip](image2)

Figure 1. Acid etching characteristics at different acid injection stages.

3.1.2. Conductivity Evaluation of Complex Fractures. On the basis of the above acid etching experiment, conductivity of etched fractures has been measured. From Figure 2, it is seen that the maintaining capacity of fracture conductivity after large-scale acid injection is inferior for near-wellbore fractures. As the closure pressure grows, fracture conductivity declines significantly. Given this, laboratory tests of propped fracture conductivity after acid etching have been carried out,
in which 50 g and 100 g of proppants (30/50 mesh) are placed across the rock sheet and conductivity variation features of acid etched rock sheets with varied proppant concentrations are experimentally captured. Results show that the rock sheets, with 50 g of proppants laid after acid etching, are able to present conductivity up to 190 $\mu$m$^2$·cm even under the closure pressure of 60 MPa, which indicates great enhancement of the maintaining capacity of fracture conductivity. On the basis of these fracture conductivity experiments, a composite network fracturing approach, combining acid fracturing and propped fracturing and moreover suitable for deep Ordovician buried-hill reservoirs, has been proposed.

![Figure 2. Fracture conductivity variation with different reservoir stimulation practices.](image)

3.2. Research on the Prepad-cooling Multi-stage Temporary-plugging Technique

The reservoir temperature of Well AT1x is up to 177°C, and the reservoir matrix is seen with poor physical properties, with fractures serving as the main storage space and flow channel, which indicates an ultra-high-temperature, deep, naturally-fractured carbonate reservoir. In present China, the main reservoir stimulation techniques such as deep-penetration acid fracturing have come into being, with respect to fractured-vuggy carbonate oil and gas reservoirs represented by the Tahe oilfield and dissolution-pore carbonate oil and gas reservoirs represented by the Sichuan Longwangmiao gas reservoir, which facilitate effective exploitation of these types of reservoirs. Nonetheless, successful reservoir simulation treatments in naturally-fractured carbonate reservoirs are still less reported. On the basis of the concept and method of network fracturing in shale and also the features of carbonate reservoirs, this paper proposes the reservoir stimulation approach integrating “deep-penetration communication and volumetric stimulation”. From a technical point of view, multi-scale natural fractures are developed in the reservoir, and it is difficult to etch and connect fractures at different scales under ultra-high temperatures, so as to expand the effectively stimulated volume; in the meantime, the target zone of stimulation has a large span, which results in great challenges for vertically uniform reservoir stimulation. Accordingly, the appropriate high-temperature-tolerable acid fracturing fluid system and fracturing practice are needed to ensure successful operation and high and stable production of Well AT1x.

3.2.1. The Prepad-cooling Technique. In order to slow down acid-rock reaction and extend the effective stimulated distance of acid, optimization is carried out in two aspects, namely the stimulation practice and acid system. First, the formation is cooled down by injecting a large volume of prepad fluids, and simulation suggests the best formation cooling performance occurs and within the effective stimulated distance of acid, the temperature is kept around 130°C, when the injection volume of fracturing fluids reaches 250 m$^3$ (Figure 3).
3.2.2. The Temporary Plugging and Fluid Diversion Technique. Natural fractures in the study area include both mostly-filled and partially-filled micro and fine cracks, and also large-scale near-wellbore fractures. It is required to achieve fluid (hydraulic fracture) diversion within the layer to improve natural fracture complexity and create fracture networks. Furthermore, the stimulation target section has a vertical span over 100 m, which demands inter-layer temporary plugging to enhance overall vertical recovery and fulfill the technical goal of three-dimensional reservoir stimulation. Within-layer diversion is to achieve dissolution and connection of natural fractures at different scales. For micro and fine cracks, low-viscosity slickwater is first injected at high pump rates to activate natural fractures and meanwhile cool down the formation, according to the results of the full three-dimensional hydraulic fracturing physical simulation experiment. Then, low-viscosity VES diversion acid is pumped into the formation also at high rates to dissolve and connect natural fractures, and build the natural fracture flow channels combing “hydraulic fracture networks and acid etching wormhole networks”. In terms of the large-scale natural fracture, deep connection is achieved mainly by alternately injecting highly viscous fracturing fluids and acid solutions.

With respect to inter-layer temporary plugging, it is realized primarily by carrying a certain quantity of degradable temporary-plugging balls with acid solutions into the perforation tunnels of the layers that have received acid solutions and then sealing these perforation tunnels. By doing so, acid solutions are subsequently diverted to low-permeability layers, and the process is repeated for uniform acid placement. Regarding this technique practice, experimental studies of degradation performance and sealing capacity of fiber temporary plugging balls are conducted, which provide references for optimization of fibers and fiber temporary plugging balls.

4. Field Application and Performance Evaluation

Fracturing testing and main fracturing operation have been conducted in Well AT1x successively. Through the analysis of minifrac treatment, it is determined that the fracture extension friction resistance is about 1.3 MPa; the leakoff coefficient is 1.1; the fracture extension stress gradient is higher than those of the high-production reservoirs in previous cases of China; the pressure difference between two shut-in pressures is about 5 MPa, and the pressure decline rate drops from 14.6 MPa/h in the first shut-in to 9.4 MPa/h, while the pressure grows from 24.7 MPa to 30.4 MPa. The last observation implies that the scale of the good natural fracture development zone is limited, and dominated by tiny fractures. In the field, the reservoir (fracture) connection performance is improved by raising up the acid concentration and also pump rate, and the pressure drop is about 12 MPa. Fracturing testing suggests that continuous operation may lead to further elevation in operation pressures and it would be difficult to enable high-pump-rate operation and go against high production. The main fracturing operation adopts a large-scale plan involving 3,000 m³ fluids, and one-time injection to improve the fracture connection distance and fracture network complexity. During the
main fracturing operation, on the basis of the operation pressure variation and microseismic monitoring results, the originally designed five-stage injection is changed into three-stage; the original four stages of temporary plugging agents and proppants are changed into three stages; pump rates, proppant concentration and fluid properties are adjusted accordingly. By doing so, we manages to implement safe and highly efficient operation over six hours under various unfavorable conditions such as operation pressures over 90 MPa, a maximum pump rate up to 11 m³/min and an injection fluid volume up to 2,500 m³. 21.5 m³ of proppants are injected, and the phenomenon, displayed as sudden pressure drops under stable-pump-rate conditions and suggesting fracture connection, occurs for five times during operation, with the maximum pressure drop of 23 MPa. The designed goals of deep connection have been fulfilled.

The microseismic monitoring result shows that the length of the artificial fracture is 280–350 m; the fracture height, 140–160 m; the width of the fracture network, nearly 200 m; the stimulated reservoir volume is expanded by 3.5 times, compared with those in previous cases. The three-dimensional reservoir stimulation is achieved, and the goal of design optimization is fulfilled. The operation achieves the design goal of integration between exploration and exploitation, and between geology and engineering, and is ground-breaking for exploration of Yangshuixiu buried hill structures. It overcomes the technical bottlenecks in achieving high and stable production in this block, and provides technical support to future reservoir stimulation in this buried hill reservoirs.

Acknowledgments
This research is supported by the CNPC Science and Technology Major Project (2017E-15) and the National Science and Technology Major Project (2017ZX05030-05) of China.

References
[1] Zhao Xianzheng, Wang Quan, Jin Fengming, et al. Re-exploration Program for Petroleum-rich Sags and its Significance in Bohai Bay Basin, East China[J]. Petroleum Exploration and Development, 2015, 42(6): 723-733.
[2] Zhao Xianzheng, Zhu Jieqiong, Zhang Ruifeng, et al. Characteristics and Exploration Potential of Tight Calcilutite Rudstone in Shulu sag, Jizhong Depression, North China reservoirs [J]. Acta Petrolei Sincia, 2014,35(4):613-622.
[3] Cai Bo,Zhao Xianzheng,Shen Hua.Hybrid Stimulated Reservoir Volume Technology for Tight oil in Shulu sag[J]. Acta Petrolei Sincia, 2015 , 36(S1):76-82 , 90.
[4] Zhao Xianzheng, Jin Fengming. Precise Buried-hill Hydrocarbon Reservoir of Exploration Hydrocarbon of Subtle Enriched Depressions[M]. Beijing: Petroleum Industry Press, 2010
[5] Bale A, Smith M B, Klein H H.Stimulation of Carbonates Combining Acid Fracturing with Proppant (CAPF): a Revolutionary Approach for Enhancement of Final Fracture Conductivity and Effective Fracture Half-length[R].SPE 134307,2010
[6] Wang Yonghui,Lu Yongjun,Li Yongping,et al. Progress and Application of Hydraulic Fracturing Technology in Unconventional Reservoir[J]. Acta Petrolei Sincia, 2012 ,33(s1): 149-158.
[7] Ming, T. Design and Application of Expandable Casing Drilling Technology of Deepsidetrack Horizontal well in Tahe Oilfield[R].IPTC 16760,2013