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Research Article

# Latest research progresses in network fracturing theories and technologies for shale gas reservoirs☆,☆☆

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**Abstract**

In view of the bottleneck of shale gas development technologies, the latest progresses in such theories on the fields like fracture network fracability evaluation, fracture network propagation mechanism, stimulated reservoir volume (SRV) evaluation and fracturing fluid research & development were analyzed comprehensively in reference to the existing achievements and experiences in North American shale gas reservoir development and based on the probes, practices and cognitions of shale gas development technologies in China since 2005. First, the study on the shale brittleness develops from the definition of mineral and mechanical semi-quantitative threshold measurement to a comprehensive evaluation which integrates rock constituents, elastic mechanics and development characteristics of natural fractures together. Second, the study on the fracture network development develops from the directional extension theory to the simulation of fracture network formation in the stochastic distribution pattern of natural fractures. Third, the study on SRV develops from the micro-seismic monitoring based instrument and technology to the mathematical theory evaluation method dependent on the discrete fracture network and extended finite element. And fourth, the study on fracturing fluids develops from the wide application of slick water (drag reducing water) and a linear gel fracturing fluid system to the development and application of novel fracturing fluids with little or no water. Then, the theoretical and technological challenges were pointed out, including the comprehensive fracability evaluation of reservoir fracture networks, the deep seated shale gas fracturing, the operation curve diagnosis of shale gas fracturing, the shale gas refracturing theory, and the research & development and flowback control of novel fracturing fluids. Finally, the development trend of related technologies was predicted so as to provide a theoretical and technical guidance for the efficient shale gas development in China in the future.


*Keywords:* China; Shale gas; Reservoir; Network fracturing; Fracability; Fracture network development; Stimulated reservoir volume (SRV); Fracturing fluid; Research progress

## 1. Shale gas development status

It can be seen from the development status of the world's technically recoverable resources of shale gas in leading countries (Table 1) that only the United States, Canada, China and Argentina have realized the commercial development of shale gas, subject to development costs, development technology and environmental issues. The technically recoverable resources of shale gas in China is the largest, while the annual shale gas production was only $78.82 \times 10^8$ m$^3$ by the end of 2016, showing a significant gap with the United States. Moreover, there are large shale gas production differences

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Table 1
Global shale gas development.

| Country | Technically recoverable resources/$10^{12}$ $m^3$ | Annual production in 2016/$10^8$ $m^3$ | Current status of exploitation |
|---|---|---|---|
| China | 31.56 | 78.82 | Commercial development |
| Argentina | 22.71 | 18.62 | Commercial development |
| Algeria | 20.02 | | Suspended in 2014 due to environmental issues and re-planned in October 2017 |
| USA | 18.83 | 4447.00 | Commercial development |
| Canada | 16.23 | 55.8 | Commercial development |
| Mexico | 15.43 | | Conventional natural gas is in dominated production, and the development of shale gas is slow. |
| Australia | 12.37 | | Shale gas exploration is at its initial stage |
| South Africa | 11.04 | | Strong willingness to develop, did not start due to environmental issues |
| Russia | 8.07 | | Emphasis on conventional natural gas development, not involved in shale gas |
| Brazil | 6.94 | | Not started due to cost issues |

between shale gas fields or demonstration areas such as Weiyuan, Changning, Zhaotong, and Jiaoshiba [1]. Nearly half of the perforation clusters show no incremental production, which is related to the implementation of shale fracturing process. Therefore, the development and innovation of fracturing technology for shale gas reservoirs have been the core strategy for shale gas stimulation in China. In view of the bottleneck of shale gas development technologies, the latest progresses in such theories on the fields like fracture network fracability evaluation, fracturing network propagation mechanism, stimulated reservoir volume (SRV) evaluation and fracturing fluid research & development were analyzed comprehensively in reference to the existing achievements and experiences in North American shale gas reservoir development [2−19] and based on the probes, practices and cognitions of shale gas development technologies in China since 2005 [20−61]. The network fracturing theories and technical system of shale gas reservoirs are developed and improved, providing theoretical and technical guidance for the future efficient shale gas development in China.

## 2. Key technologies for shale gas reservoir fracturing

To achieve economic productivity of shale gas reservoirs, hydraulic fracturing is required to change the stress disturbance degree between wells, intervals, and clusters, so as to create sufficient fractures [48]. Horizontal staged multi-cluster fracturing, synchronous fracturing, zipper fracturing and refracturing are the key technologies in the successful commercial development of shale gas at home and abroad.

### *2.1. Horizontal well staged multi-cluster fracturing technology*

Horizontal staged multi-cluster fracturing technology is currently the main technology for shale gas fracturing stimulation. Staged multi-cluster perforation is used for the superposition of stress disturbances of multiple cluster fractures, to improve the hydraulic fracturing propagation pattern, expand the fracturing extension area, and increase the stimulated reservoir volume, and the single well recovery increment can be 35% [6]. Considering the differences in geological characteristics, process optimization and adjustment strategy of "One well, one strategy; one interval, one strategy" was proposed in field operation. Proper strategies were proposed for the technical difficulties in prepad fluid stage, sand-adding stage, and shale gas well drilling of middle and deep layers, and eventually staged multi-cluster fracturing technology was developed, which is suitable for fracturing operation in China, and has greatly reduced operating costs and risks.

### *2.2. Synchronous fracturing technology*

Synchronous fracturing technique was proposed in view of the limitation of horizontal staged multi-cluster fracturing in a single well. Multistage fracturing was made synchronously in two or more wells to increase the complexity of interwell fracturing development and maximize the stimulated volume (SRV), reduce the operation cost and shorten the operation period. This technology and the zipper fracturing technology mentioned later, etc.) is one of the means of factory operation mode of the platform well group (Fig. 1). In this way, the operation cost per well in shallow layers, the burial depth of which are less than 3500 m, is reduced by 33%, and the operation time is shortened by 196 days [1]. With this synchronous fracturing technology, the production in Barnett Shale in North America and Jiaoshiba Shale Gas Field of Sinopec in Fuling have been increased by 1.62 and 2.36 times, respectively (Fig. 2).

### *2.3. Zipper fracturing technology*

Zipper fracturing technology is similar to synchronous fracturing and alternating fracturing ("Texas Two Step"), with a short operation period and a large superposition range of stress disturbance. The difference lies in the fracturing sequence between adjacent wells or multiple wells, which is performed like a zipper [31] (Fig. 1). Zipper fracturing technology was applied in Wells H3-1 and H3-2 in the Changning H3 pad of CNPC, and Fuling JY30 and JY33 pads of Sinopec. The operation period was reduced by 30%−40%, and the SRV was increased by 50% compared to the single well fracturing