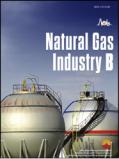
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Research Article

Exploration, development, and construction in the Fuling national shale gas demonstration area in Chongqing: Progress and prospects\*

Xusheng Guoa, Degao Hub, Zhiguo Shub, Yuping Lic, Aiwei Zhengb, Xiangfeng Weic, Kai Nic, Peirong Zhaoa & Jing Caia,\*

1. Sinopec Oilfield Exploration & Development Department, Beijing 100728, China b Sinopec Jianghan Oilfield Company, Qianjiang, Hubei 433124, China

c Sinopec Exploration Company, Chengdu, Sichuan 610041, China

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Abstract

In September 2013, the National Energy Administration approved the establishment of Fuling national shale gas demonstration area (hereinafter referred to as the demonstration area), whose construction was completed in December 2015. After nearly one decade of devel-opment, it has grown into the main shale gas production base in China. In order to speed up the integration and breakthrough of China's shale gas theoretical understanding and exploration and development technology and effectively promote the great development of marine shale gas in China, this paper reviews and summarizes the development and construction history of the demonstration area, geological theory understanding, engineering technology and key equipment progress. And based on this, the future development direction of the demonstration area is predicted. And the following research results are obtained. First, shale gas exploration and development in the demonstration area is divided into three stages, i.e., exploration evaluation, phase I and II construction, and stacked development and adjustment. Second, the “binary enrichment” theory for marine shale gas and the engineering theory for efficiently developing gas reservoirs are innovatively established. Third, a series of sup-porting technologies are innovatively developed, such as optimized and fast drilling technology for shale gas cluster horizontal wells, differ-entiated network fracturing technology, high-efficiency gas production, gathering and transportation technology, and green development technology for karst mountains, and the localization of key equipment and tools is realized. Fourth, the efficient development of shallow overpressure shale gas reservoirs above 3500 m in depth and the effective development of shale gas reservoirs at the depth of 3500e4000 m are realized in the demonstration area. Fifth, the construction of the demonstration area in the future includes accelerating the development of normal-pressure deep shale gas, continuously tackling key shale gas EOR technologies, actively promoting the field application of new tech-nologies and methods, and powerfully strengthening the construction of green demonstration areas. In conclusion, this demonstration area is the earliest one of four national shale gas demonstration areas, and its achievements will provide continuous guidance for the shale gas exploration and development in China and play a demonstrative and guiding role in promoting the development of shale gas geological theories and exploration and development technologies in China.

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Keywords: Chongqing; Fuling national shale gas demonstration area; Construction history; Theoretical understanding; Technical progress; Prospect

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* Corresponding author.

E-mail address: [caijing.jhyt@sinopec.com](mailto:caijing.jhyt@sinopec.com) (Jing Cai).

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1. Introduction

China is rich in shale gas resources, with a national shale gas geological resource amount of 134.42 1012 m3, showing great exploration and development potential. China Petroleum

* Chemical Corporation (hereinafter referred to as Sinopec) attaches great importance to the exploration and development of shale gas. In 2006, Sinopec launched the research project

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| X Guo et al. / Natural Gas Industry B 10 (2023) 62e72 | 63 |

Early Analysis on Resource Potential of Shale Gas in China. Based on systematic investigation of the formation, enrich-ment, and development of shale gas in typical shale gas basins in the United States, this project compared and analyzed the formation conditions of shale gas in China and around the world, and evaluated the prospects of shale gas resources in China. In 2009, Sinopec established a professional manage-ment organization as well as an exploration and development team for unconventional energy. Then, by drawing on expe-rience from North America, Sinopec confirmed the evaluation parameters for selecting shale gas areas, evaluated the poten-tial areas for marine shale gas exploration in southern China, and drilled wells Xuanye 1, Heye 1, and Huangye 1 succes-sively. Since 2011, Sinopec has shifted its exploration focus from marine shale gas in southern China to the Sichuan Basin and its periphery, selected the Longmaxi Formation in the Jiaoshiba area in Fuling, Chongqing as the most favorable exploration target, and implemented Well Jiaoye 1. In November 2012, the daily gas testing production of Well Jiaoye 1HF reached 20.3 104 m3, and the Fuling Shale Gas Field was discovered.

In September 2013, the National Energy Administration approved the establishment of the Chongqing Fuling National Shale Gas Demonstration Area (hereinafter referred to as the Fuling National Shale Gas Demonstration Area). In the early stage of constructing the Fuling National Shale Gas Demon-stration Area, facing difficulties such as complex surface conditions, strong structural deformation, great burial depth, and no experience to learn from, Sinopec adhered to the practice of exploring boldly and making progress despite difficulties and. Since then, major breakthroughs have been made in aspects including exploration and development the-ory, the organizational production model, and green develop-ment, and the Fuling National Shale Gas Demonstration Area was quickly and successfully built with high technical level and high construction quality, making China the third country to develop shale gas at a large scale after the United States and Canada. The construction of the Fuling National Shale Gas Demonstration Area will help promote the large-scale increase in shale gas reserves and the construction of profitable pro-duction, and lead the high-quality construction of national-level shale gas demonstration areas in locations such as Changning-Weiyuan, Zhaotong, and Yan'an, which are of great significance in accelerating the industrialization of shale gas, developing clean energy in the form of shale gas, pro-moting energy production and consumption structure, and ensuring national energy security [[1](#page1),[2](#page1)].

2. Construction process of the demonstration area

The construction process of the demonstration area can be divided into three main stages as shown in [Fig. 1](#page1).

2.1. Exploration and evaluation stage

The exploration and evaluation stage ranged from 2009 to 2012. In this stage, based on comparison with the typical shale

gas formation conditions in North America, it was clear that shale thickness, organic matter abundance, thermal evolution degree, burial depth, and mineral content are the main pa-rameters for evaluating marine shale gas, and Well Jiaoye 1HF was deployed in the Jiaoshiba structure. In November 2012, the daily gas testing production of Well Jiaoye 1HF reached 20.3 104 m3, and the Fuling Shale Gas Field was discovered.

2.2. Phase I and phase II productivity construction stage

This stage ranged from 2013 to 2017. In 2013, in accordance with the idea of integrated exploration and development, a three-dimensional (3D) seismic survey with an area of 594.5 km2 was deployed to confirm the structural details of the Jiaoshiba anticline and the distribution characteristics of shale in the Longmaxi Formation. At the same time, three exploratory wells, Jiaoye 2, Jiaoye 3, and Jiaoye 4, were deployed, which successively obtained high-production gas flow and thus ach-ieved overall control in the main body of the Jiaoshiba anticline. In terms of development, Well Jiaoye 1HF was transferred to trial production to evaluate single-well productivity, and the evaluation of the test well group was initiated, with a newly built productivity of 5.0 108 m3/a, achieving construction productivity, being put into production, and taking effect in the same year. In 2014, Phase I productivity construction of

1. 108 m3/a began, and on July 10 of the same year, the Fuling Shale Gas Field reported the first proven geological reserves of shale gas in China, with newly added proven

geological reserves of 1067.5 108 m3. In December 2015, the

Fuling Shale Gas Field had cumulative built productivity of

1. 108 m3/a, with cumulative newly added proven geological reserves of 3806 108 m3, and the construction project of the Fuling National Shale Gas Demonstration Area was accepted by the National Energy Administration.

At the same time as the main body of the Jiaoshiba anti-

cline was being evaluated, four exploratory wells and a 3D seismic survey area of 550 km2 were deployed in the complex structural areas around the Jiaoshiba anticline. A high-

production shale gas flow of 20.9 104 m3/d was drilled in Well Jiaoye 8, achieving a major breakthrough in Phase II shale gas exploration in the Fuling Pingqiao anticline. In January 2016, 50 108 m3/a of productivity construction for Phase II in the Jiangdong and Pingqiao blocks of the Fuling Shale Gas Field was started. In March 2017, the cumulative production of the Fuling Shale Gas Field exceeded

1. 108 m3. In December 2017, construction of the Fuling Shale Gas Exploration and Development Demonstration Base was successfully completed.

2.3. Stacked development, adjustment and construction stage

This stage has ranged from 2018 to the present. In May 2018, workers in the Fuling Shale Gas Field started development and adjustment testing in the Jiaoshiba block, prepared an overall development adjustment plan, and deployed a total of 244 development adjustment wells. At the same time, in the Fuling

64 X Guo et al. / Natural Gas Industry B 10 (2023) 62e72

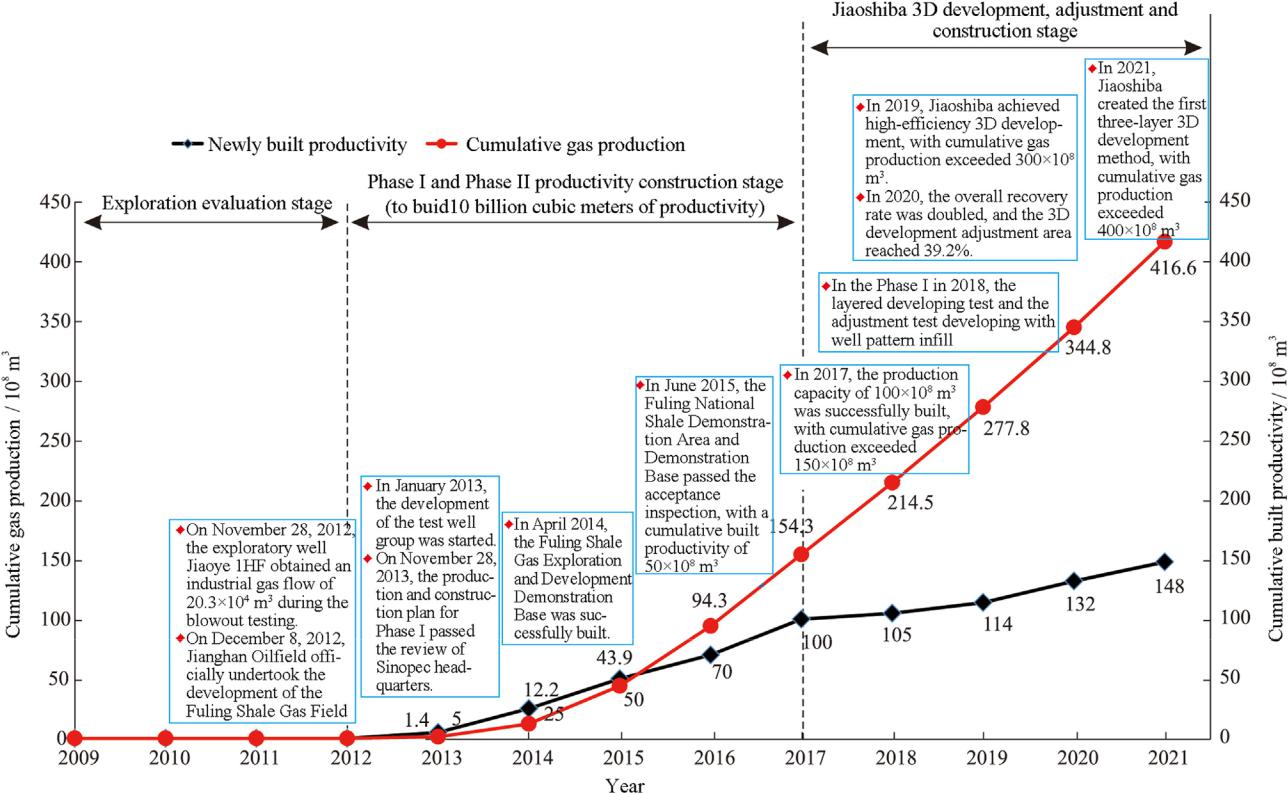


Fig. 1. Construction process of the Fuling National Shale Gas Demonstration Area.

Shale Gas Field, exploration in peripheral normal-pressure shale gas areas and low-cost technological research were strengthened, and the gas field took the lead in realizing large-scale verification of normal-pressure shale gas in China, with newly added proven geological reserves of 2967 108 m3 in the western DongshengePingqiao block and Baima block.

As of December 2021, 650 wells had been opened in the Fuling National Shale Gas Demonstration Area, with cumu-lative proven shale gas reserves of 8975 108 m3, cumulative newly built productivity of 148 108 m3/a, and cumulative gas production of 416.6 108 m3, becoming the main force for the production growth of domestic shale gas in China.

1. Theoretical understanding of exploration and development in the Fuling Shale Gas Field

Compared with gas fields in North America, the Fuling Shale Gas Field is characterized by an old formation age, a high degree of thermal evolution, strong tectonic deformation, great burial depth, and complex surface conditions, which make effective production difficult [[3](#page1)]. In view of the char-acteristics of the marine shales of the Wufeng FormationeLongmaxi Formation in the Fuling area, based on independent innovation, Sinopec adopted the method of inte-grating theory, practice, laboratory research, and field appli-cation, and developed the binary enrichment theory for marine shale gas and the engineering evaluation method for efficient development of shale gas reservoirs.

3.1. Basic geological characteristics

The Fuling Shale Gas Field is located at the junction of several structural units, such as the Shizhu synclinorium, the Fangdoushan anticlinorium, and the Wanxian synclinorium in the southern part of the east Sichuan barrier fold belt in the Sichuan Basin. The Wufeng Formation and the first member of the Longmaxi Formation comprise the main series of layers for development, and are vertically distributed continuously with no obvious interlayers. In the Wufeng Formation and the first submember of the first member in the Longmaxi For-mation, the high-quality shale layers of deep-water shelf facies are 30e45 m thick, with an average TOC content of 3.5%, an average porosity ranging from 4.4% to 6.2%, and an average siliceous mineral content of 45.7%, showing the “three high” characteristics of high carbon, high porosity, and high silicon as a whole [[4](#page1)e[6](#page1)].

The Wufeng Formation and the first member of the Long-maxi Formation are characterized by a layered distribution with a large area and overall gas-bearing properties. It was calculated that in the Wufeng Formation and the first member of the Longmaxi Formation, cracked gas from the retained oil in shale gas layers accounts for about 70% of the shale gas, and cracked gas from kerogen accounts for about 30% of the shale gas, revealing that the shale gas in the gas field has the characteristics of “source-reservoir integration, in-situ reten-tion” [[7](#page1),[8](#page1)]. The burial depths of the gas reservoirs range from 1800 m to 4500 m, the formation pressure coefficient ranges

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| X Guo et al. / Natural Gas Industry B 10 (2023) 62e72 | 65 |

from 1.05 to 1.58, and the geothermal gradient ranges from 2.36 to 2.62 C/100 m, showing the characteristics of gas reservoirs with middle-deep layers, a normal geothermal temperature, and normal-high pressure. The relative density of natural gas in the gas reservoir is between 0.559 and 0.601, which indicates high-quality natural gas with an average methane content of 98.49%, average carbon dioxide content of 0.5%, and average helium content of 0.045%, without H2S.

3.2. Binary enrichment theory for marine shale gas

3.2.1. Development of high-quality shale in deep-water shelf facies as the basis for hydrocarbon generation and storage control of shale gas

By analyzing the sedimentary characteristics, geochemical characteristics, and genesis model of the main shale in southern China, it was found that the deep-water shelf shale had high organic carbon content and endogenous siliceous mineral content, which show a strong positive correlation. The organic carbon content in the deep-water shelf shale is posi-tively correlated with the amount of hydrocarbon generation and pore volume, and the brittleness of the shale is good, which is beneficial to shale gas generation, storage, and fracturing [[9](#page1)e[11](#page1)].

3.2.2. Good preservation conditions are key for hydrocarbon accumulation and production control of shale gas

A shale formation assemblage with high roof and floor breakthrough pressures can effectively prevent the vertical dissipation of hydrocarbons from the beginning of hydrocar-bon generation, which is beneficial to the retention, phase transformation, and pressure maintenance of liquid hydrocar-bons. Through triaxial physical simulation experiments and pressure sensitivity analysis on permeability, it was found that the sealing performance of shale becomes worse as the burial depth becomes shallower, revealing the dynamic preservation mechanism of shale gas; that is, retention in the early stage and reformation in the later stage. A preservation-escape model for shale gas was established, and areas with good roof and floor conditions, moderate burial depths, and loca-tions far from denudation outcrops and open faults are considered to have good preservation conditions favorable for shale gas enrichment [[12](#page1)e[16](#page1)].

3.3. Engineering theory for efficient development of shale gas reservoirs

3.3.1. Flow mechanism of a multi-scale shale medium Because of the multi-scale porous medium, multi-phase

fluid occurrence, and complex coupling relationships in shale formation, understanding of the flow mechanism and laws of shale gas in the porous medium is not yet clear. Through research and development of various types of experimental equipment and testing methods, such as poros-ityepermeabilityesaturation testing and production simula-tion suitable for the characteristics of shale reservoirs, multi-

phase, multi-mechanism flow experimental technology simu-lating reservoir conditions and development processes was established, and was used to reveal the laws of desorption, diffusion, and flow during shale gas development in the Fuling Demonstration Area. During the depressurized production process of shale gas, the produced gas is mainly free gas in the initial stage, and the contribution of adsorbed gas gradually increases [[17](#page1)e[20](#page1)]. Under the temperature and pressure con-ditions in the shale reservoir in the Longmaxi Formation (82 C, 37.7 MPa), Darcy flow dominates in pores larger than 100 nm, slip flow dominates in pores within 20e100 nm, and slip flow and transition flow dominate in pores within 1e20 nm.

3.3.2. Evaluation, dynamic analysis, and prediction of the productivity of shale gas wells

Nature dynamic analysis methods for shale gas production laws are lacking, and it is difficult to accurately evaluate the productivity of shale gas wells with conventional methods. Through analysis, it has been clarified that the production of shale gas wells in the Fuling Demonstration Area includes three stages: stable production with declining pressure, declining production with constant pressure, and production with increasing pressure ([Fig. 2](#page1)). The stable production stage with declining pressure shows the characteristics of unsteady linear flow, and the normalized productionemass equilibrium time has a clear 1/2-line segment in the logelog graph. The declining production stage with constant pressure generally conforms to the law of harmonious decline [[21](#page1)], and the estimated decline rate in the first year in different regions ranged from 56.1% to 66.8%, with an average of 60.5%.

1. Engineering technology progress in the Fuling Shale Gas Field

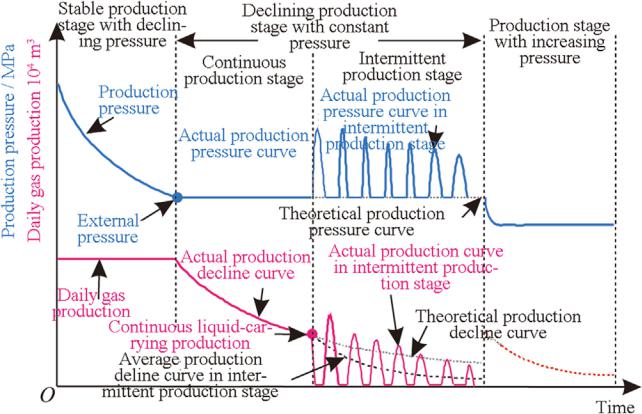
To solve the severe problems in the production of the Fuling Shale Gas Demonstration Area, by combining inde-pendent development with technical import, and through re-searches and practices, four major supporting technology systems with Fuling shale gas characteristics have been innovated and developed: optimal and fast drilling technology for shale gas cluster horizontal well groups, distinguished fracture network fracturing technology for shale reservoirs with different geological conditions, high-efficiency shale gas collection and transportation technology, and green develop-ment technology for shale gas in karst mountainous areas. During implementation of these technologies, key equipment and supporting tools were successfully localized.

4.1. Optimal and fast drilling technology for shale gas cluster horizontal well groups

The Fuling Shale Gas Field is in a typical mountainous terrain, with a high leakage risk in the superficial karst land-forms. The locations of well sites are limited by the terrain; therefore, there typically are large offset distances for cluster well groups [[22](#page1)e[24](#page1)]. Through laboratory tests, research and

66 X Guo et al. / Natural Gas Industry B 10 (2023) 62e72

Fig. 2. Production model of shale gas for staged fracturing horizontal wells in the Fuling Gas Field.



development of key tools, and other efforts, a series of high-efficiency drilling technologies for cluster horizontal well groups in mountainous environments were established, which greatly reduced the drilling period e the average drilling period of a well with a depth of 4500 m was reduced to 49 days, and the shortest drilling period was 25.69 days.

4.1.1. Drilling optimization and design technology for horizontal wells in the Fuling Shale Gas Field

Using logging data and the formation petrophysical parameter model corrected by the core mechanical parameters, a “three pressure” profile of the shale formation in the demonstration area was established, and the collapse pressure characteristics of the wellbore trajectory under the action of bedding occurrence, fluid invasion, and other factors were clarified, which laid a foundation for the optimization and design of the wellbore structure. Combined with the reservoir stimulation mechanism, the variation law of formation pres-sure and collapse pressure in old wells after fracturing was simulated to guide the design of safe drilling fluid density for new wells with complex well patterns. On this basis, the wellbore structure design of a conduit with three sections in complex structural areas was further optimized, and the structure design of a conduit with two sections was promoted in structurally stable areas, which both promoted drilling speed and cost reduction. A trajectory optimization method with the shortest period and minimum footage as the objective function was established, and trajectory models such as “five points and six segments” and “dual two dimensions” were proposed. In addition, the design method of a cross-well layout with a fishhook profile was innovated. As a result, the blind area during the drilling process was reduced by 85.7%, real-izing the effective utilization of resources.

4.1.2. High-efficiency drilling mode of a “well factory” for shale gas in a complex mountainous environment

Through the “well factory” operation process and process optimization, Fuling Shale Gas Field workers established technical specifications for well factory drilling operations in

this mountainous environment, achieved efficient drilling and reuse of drilling fluids, and promoted application of the “learning curve” [[25](#page1)e[27](#page1)]. As a result, the average drilling period was shortened by 32% compared with the initial period, and the drilling cost was reduced by 33.8%. Furthermore, Fuling Shale Gas Field workers also developed high-efficiency drill bit sequences, such as large-size PDC, directional PDC, hybrid drill bits, and shale horizontal drill bits, as well as key tools such as the hydraulic oscillator and torsional impactor. The 1411 drilling speed-up template and wellbore trajectory fine control technology were established, centering on high clear water drilling in the upper part, “directional PDC/hybrid bit þ MWD þ even wall thickness screw,” and “low-cost domestic oil-based drilling fluid þ domestic LWD þ oil-resistant long-life screw” ([Table 1](#page1)). The proportion of drilling in one trip in the horizontal section reached 40%, and con-ventional steering tools were used in more than 270 wells on site, saving 65% of the steering cost, and realizing the full localization of key tools and equipment for shale gas drilling.

4.1.3. Cementing technology for horizontal wells with a long lateral section

The elastic and ductile latex cementing slurry system was developed by studying the failure mechanism of the cement sheath, optimizing cement slurry additives, and evaluating the performance of cement for long-term sealing and resistance to alternating loads. The oil-based drilling fluid, cementing flushing fluid, and cleaning fluid system were developed by evaluating the oil-based wetting reversal, optimizing the mo-lecular structure design of the solubilizing high-efficiency flushing agent, and optimally selecting the weighting mate-rial. Key completion tools specialized for shale gas, such as gas-sealed high-strength casing, a resin centralizer, a self-rotating guide shoe, and a toe end sliding sleeve, were developed, and prestressed cementing technology for long horizontal wells centered on wellbore preparation, casing running, centering, and efficient replacement was established. As a result, the high-quality cementing rate reached 100%, and the annular pressure dropped to 8.6% after fracturing.

4.2. Distinguished fracture network fracturing technology for shale reservoirs with different geological conditions

Compared with shales in North America, the shale gas reservoirs in the Fuling demonstration area are complex in geological conditions, with variable burial depths and struc-tural morphology, as well as distinguished in-situ stress and fracture distribution conditions. Accordingly, three core tech-nologies have been created for complex shale reservoirs: distinguished fracture network fracturing technology, refrac-turing technology for shale gas horizontal wells, and multi-method comprehensive evaluation after fracturing. These technologies have guided plan design and construction for more than 600 wells, with a fracturing success rate of 98% and an effective rate of 97%.

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|  | X Guo et al. / Natural Gas Industry B 10 (2023) 62e72 | | |  | 67 |
| Table 1 |  |  |  |  |  |
| One-trip drilling technology template for the Fuling Shale Gas Field. | | |  |  |  |
|  |  |  |  |  |  |
| Section | Formation | Wellbore size/mm | Bit | Parameter | Trip |
|  |  |  |  |  |  |
| Spud | Jialingjiang Formation | 406.4 | KS1662SGAR | Focus on strengthening displacement | 1 |
| Second section | Feixianguan Formation-Changxing Formation | 311.2 | KM1653DAR | Focus on strengthening drilling pressure | 4 |
|  | Longtan Formation-Maokou Formation | 311.2 | HJT637GK | Focus on strengthening displacement | 4 |
|  | Qixia Formation-Hanjiadian Formation | 311.2 | KMD1663DFRT | Focus on strengthening rotate speed | 4 |
|  | Hanjiadian Formation-Xiaoheba Formation | 311.2 (directional) | KSD1362ADGR | Focus on strengthening rotate speed | 4 |
| Third section | Xiaoheba Formation-Longmaxi Formation | 215.9 (directional) | KPM1642ART | Focus on strengthening drilling pressure | 1 |
|  | Longmaxi Formation, Wufeng Formation | 215.9 | KSD1652ADGR | Focus on strengthening rotate speed | 1 |
|  |  |  |  |  |  |



4.2.1. Zoned and layered distinguished fracturing optimization and design technology

Based on the changes in characteristics of the reservoirs along the plane and vertical directions in the Fuling Shale Gas Field, and on the results of indoor multi-factor fracturing physical simulation tests, the fracture initiation and extension mechanism of shale with different degrees of brittleness and lamination development was revealed, which provided a theoretical basis for the targeted and fine plan design for shale gas wells.

With the key geological factors of different blocks in the Fuling Gas Field, a distinguished fracturing process charac-terized by plane fine design and vertical precise stimulation was carried out. On the plane, aiming to maximize the stim-ulated reservoir volume (SRV) and complicate the fracture network, the main stimulation model with mixed fracturing and combined sand addition as the core was established, and targeted stimulation strategies for different types of reservoirs were formulated ([Table 2](#page1)). Vertically, considering the char-acteristics of each small layer and the law of fracture propa-gation, the method for designing construction parameters with three major categories and six parameters was established, and the distinguished fracture network fracturing technology in different zones and small layers was formed. After the tech-nology was implemented on site, the average tested gas pro-duction of a single well reached 26 104 m3/d, which strongly supported the productivity construction of 10 billion cubic meters of shale gas in Phases I and II.

Considering the demands and relationships in various as-pects of development adjustment wells, including reservoir characteristics, well pattern, well spacing, old well induction, and economic evaluation, and with the aim of effective pro-duction of the well group as a whole, and a stimulation concept based on increased contact area and synergistic opti-mization of the well group was proposed. In addition, frac-turing technology characterized by fine fracture deployment, balanced stimulation, and high-strength sanding was estab-lished. By popularizing and applying precise fracturing tech-nology for stacked development and adjustment wells, key core parameters were improved, and the average tested gas productions of lower infill wells and upper gas layer wells were increased to 22.6 104 m3/d and 17.4 104 m3/d, respectively.

4.2.2. Refracturing technology of horizontal shale gas wells In view of the low recovery rate and the difference in the

stimulation effect in horizontal well sections, the variations of the stress field and initiation in shale gas wells, as well as the extension law of refracturing fractures, were studied, and the refracturing timing and well selection method were clarified. The Fuling Shale Gas Field has played a leading role in exploring refracturing technology for horizontal shale gas wells in China, with the development of two refracturing technology systems: temporary plugging and diversion for horizontal wells with short laterals, and rebuilding wellbore for horizontal wells with long laterals.

Table 2

Distinguished fracturing technology measures for different types of reservoirs in the Fuling Shale Gas Field.



|  |  |  |  |
| --- | --- | --- | --- |
| Zone | Main area in Jiaoshiba formation | Areas with normal and low | Areas with complex structure in |
|  |  | pressure in Baima formation | Jiangdong and Pingqiao formations |
|  |  |  |  |
| Geological Characteristics | Moderate burial depth, gentle structure, and | Well-developed natural fractures, | Increased burial depth, large |
|  | well-developed bedding fractures | moderate burial depth, high | structural changes, enhanced |
|  |  | brittleness index | plasticity |
| Fracture propagation mechanism | Conjugate shear failure of multiple fractures | Dominated by natural fracture | The failure difficulty of natural |
|  | in weak connected bedding planes or natural | induction | fractures and beddings increases, |
|  | fractures |  | and the shear zone length of the |
|  |  |  | bedding planes decreases |
| Technology measures | Dual sweet spots of geology and | Optimally select perforation | Generate fractures with high- |
|  | engineering, multi-liquid combination | location, increase net pressure with | viscosity liquid in front, increase |
|  | control near and expand far, | high displacement, divert flow by | comprehensive sand-liquid ratio |
|  | multi-level support with different particle | temporary plugging | with medium to long slugs |
|  | sizes |  |  |
|  |  |  |  |



68 X Guo et al. / Natural Gas Industry B 10 (2023) 62e72

Temporary plugging and diverting refracturing are per-formed with the aims of dredging old fractures and opening new fractures, and the compound temporary plugging method of inter-cluster plugging and in-fracture diversion is adopted for this purpose. Perforation clusters with basically the same initial pressure are divided into one grade, and the construction mode of pressurized squeeze injection and graded main pressure is adopted. This refracturing technology has been successfully applied to the short horizontal section (<500 m) of Well Jiaoye 9-2HF, with cumulative gas production of 1072 104 m3 after refracturing. The reconstructed wellbore staged fracturing [[28](#page1)] technology mainly targets insufficient stimulation between clusters in long horizontal well sections; that is, a small Ø88.9 mm casing is run in a Ø139.7 mm casing to re-cement the well and build a new wellbore ([Fig. 3](#page1)). Then, the staged perforation and fracturing method is used to find remaining reserves between sections and clusters, so as to accurately re-form the well sections with remaining potential. A field test was successfully carried out in Well Jiaoye 4HF, and the tested gas production reached 18.1 104 m3/d, which provided a new technical approach for the efficient development of old areas, and played a favorable role in promotion and demonstration.

4.2.3. Multi-method comprehensive evaluation technology for shale gas wells after fracturing

The fracture morphology in shale gas reservoirs is com-plex and variable, and there is no systematic method for

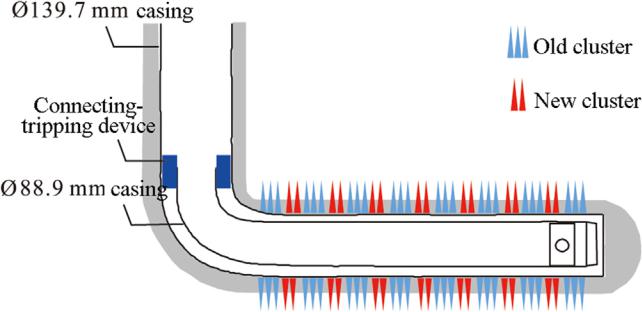


Fig. 3. Re-fracturing process of re-constructed wellbore in the Fuling Gas Field.

evaluating the fracturing effect. To address these problems, Fuling Shale Gas Field workers created a quantitative frac-ture description technology for the first time to analyze fracturing dynamics and evaluate fracturing performance in shale gas wells [[29](#page1)e[31](#page1)]. Focusing on the diagnosis and analysis of fracture morphology, expansion, and evolution, a method for quantitatively evaluating change in the fracturing construction curve was established, and the response law of the surface pressure under different fracture extension states was clarified. Using big data analysis methods such as neural networks, gray correlation, and analytic hierarchy processes, the main controlling geological and engineering factors affecting single-well productivity in different regions and the weight ranking of these factors were clarified. A variety of analysis methods ([Table 3](#page1)) were integrated and applied to quantitatively evaluate the effect of fracture network fracturing, which has been widely applied in the gas field.

4.3. High-efficiency gas gathering and transportation technology for shale gas

4.3.1. Full-life-cycle gas production technology for shale gas wells

It is difficult to predict the accumulated fluid in shale gas wellbores, and it is complex to design and optimize gas pro-duction processes. In view of these difficulties, full-life-cycle gas production technology for shale gas wells in the Fuling Shale Gas Field was innovated. Based on the production law of gas wells, with the node analysis method as the core, an optimization and design method for the wellbore integrated gas production process of the shale gas wells in the gas reservoir was developed, and a classification and staged opti-mization plan for gas production in Fuling was formulated. Aiming at the particular wellbore and wellhead structures of the shale gas wells in Fuling, a series of drainage technologies, such as cast-and-fishing gas lift valve drainage, coiled tubing completion, concentric tube completion, intelligent plunger, and pressurization combined with bubble drainage, were developed, which provided technical means for efficient pro-duction of the gas field.

Table 3

Multi-method comprehensive evaluation technology for gas wells after fracturing in the Fuling Shale Gas Field.



|  |  |  |
| --- | --- | --- |
| Evaluation method | Technical Features | Application scope |
|  |  |  |
| Numerical Simulation | Fitting after fracturing based on mathematical model | Cluster spacing, fracturing scale optimization, SRV |
|  | and engineering construction parameters | assessment |
| Productivity profile test | Quantitative analysis of gas and water production | Single-section/single-well stimulation effect |
|  | effects in different well sections |  |
| Micro seismic monitoring | Methods of surface monitoring and downhole | Extension and space distribution of artificial fractures |
|  | monitoring, real-time monitoring of fracturing | (fracture length, fracture height, fracture width) |
|  | construction |  |
| Tracer test | Effective monitoring of fracturing effects with | Fracture length monitoring in single well and its influence |
|  | alcohol tracers | on the production in offset wells |
| Big data analysis | Sensitivity analysis on influencing factors by using | Main influencing factors affecting gas well productivity |
|  | gray correlation, analytic hierarchy process, other |  |
|  | methods |  |
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| X Guo et al. / Natural Gas Industry B 10 (2023) 62e72 | 69 |

4.3.2. Surface gathering, transportation, and supporting technology with complex mountain characteristics

Based on the general ideas of standardized design, modular construction, standardized procurement, and informatization improvement, and according to the surface characteristics of the Fuling area, surface gathering, transportation, and sup-porting technology of the ring pipe network, two-level station deployment, wet gas gathering and transportation, and two-level dehydration were established. A total of 63 gas gath-ering stations and gas production platforms have been deployed in the Jiaoshiba block, with a land saving rate of 57%.

4.3.3. Building a digital shale gas demonstration area Through the construction of a communication system, se-

curity system, supervisory control and data acquisition (SCADA) system and information platform, a digital gas field characterized by high degrees of automation, visualization, integration, and routing was built. The automatic collection rate of real-time data from gas production, gathering, and transportation reached 100%; thus, the unattended operation of gas gathering stations and the active shutdown of gas wells under abnormal conditions were realized, ensuring production safety.

4.4. Green development technology for shale gas in a karst mountain region

4.4.1. Treatment technology to make the water produced during shale gas production reach the standard

Systematic research was conducted on the treatment pro-cess that makes the water produced during shale gas produc-tion reach the relevant standard. The skid-mounted produced water treatment equipment was developed. The core treatment process of pretreatment, double-membrane desalination, crystallization, and evaporation was established ([Fig. 4](#page1)). A large-scale station for treating water produced during shale gas production was built. The quality of the water treated for external drainage reached the Class III standard of the Surface Water Environmental Quality Standard, which was better than the national standard.

4.4.2. Harmless treatment technology for solid waste Devices and technologies for harmlessly treating water-

based and oil-based muds were developed, and a supervision is made on the whole process from collection, transportation, storage, to harmless treatment of muds. Two sets of modular pyrolysis treatment devices, batch type and continuous type, were developed, which achieve the hydrocarbon content in the treated pyrolysis ash of only 0.02%, better than the national standard. Furthermore, unburned bricks, fracturing proppants and other products were developed using the ash and slag, achieving 100% harmless treatment of oil-based muds.

4.4.3. Intensive land utilization technology for shale gas development in karst mountain areas

During the exploration and development process in the Fuling Shale Gas Field, land reclamation has lacked not only

systematic engineering technology, but also practical engi-neering experience that can be used for reference [[32](#page1)e[34](#page1)]. Based on the characteristics of the karst landforms, Fuling Shale Gas Field workers compiled a set of land reclamation technologies that can effectively restore and improve land productivity. The technical process includes determining the reclamation scope, dividing the reclamation units, determining the reclamation type, and determining post-evaluation methods.

4.4.4. Comprehensive carbon emission reduction technology for shale gas development

By researching and applying technologies and methods such as integrated testing and production, grid-connected electric drilling rigs, all-electric-drive high-efficiency frac-turing, and downhole throttling, gas emissions were reduced, and resources were saved, reducing the average shale gas release volume per well by 43 104 m3.

4.5. Key equipment and materials for efficient development of the demonstration area

By taking advantage of the complete industrial chain of Sinopec, the Fuling Shale Gas Demonstration Area strength-ened research and development of equipment and tools, and realized all-domestic production of key equipment and sup-porting tools for “well factory” drilling and fracturing, which effectively breaks the foreign monopoly, reduces production costs, and improves productivity.

The self-propelled drilling rig with all-around integral movement was innovated, with a maximum movement weight of 1000 t and an inter-well positioning accuracy of less than 10 mm. As a result, the inter-well relocation of the drilling rig was shortened from 72 h to 4 h. A modular, highly automated, step-by-step, track-type integral movement dril-ling rig suitable for operation in a mountainous environment was developed. Oil-resistant and long-life screw drilling tools, and friction/drag reduction tools were developed, providing complete sets of equipment and tool solutions for shale gas development. The world's first 3000-type fracturing pump truck, coiled tubing operation truck, high-pressure manifold, and other supporting equipment were innova-tively developed, forming a complete set of equipment so-lutions for shale gas development, which effectively guaranteed long-term, high-pressure, high-power fracturing operation in mountainous environments. An electric frac-turing pump with 5000 hp (1 hp ¼ 745.699 9 W) was developed.

Key tools such as an 8 kN logging tractor, special PDC bit, oil-resistant screw, high-temperature resistant and high-pressure resistant easy-drilling bridge plug, and 140 MPa multi-stage perforating tool string were developed, which reduced production costs, enabling large-scale applications. An oil-based mud system and a high-efficiency fracturing drag-reducing fluid system were innovatively developed. Technical indicators of these systems reached the international

70 X Guo et al. / Natural Gas Industry B 10 (2023) 62e72

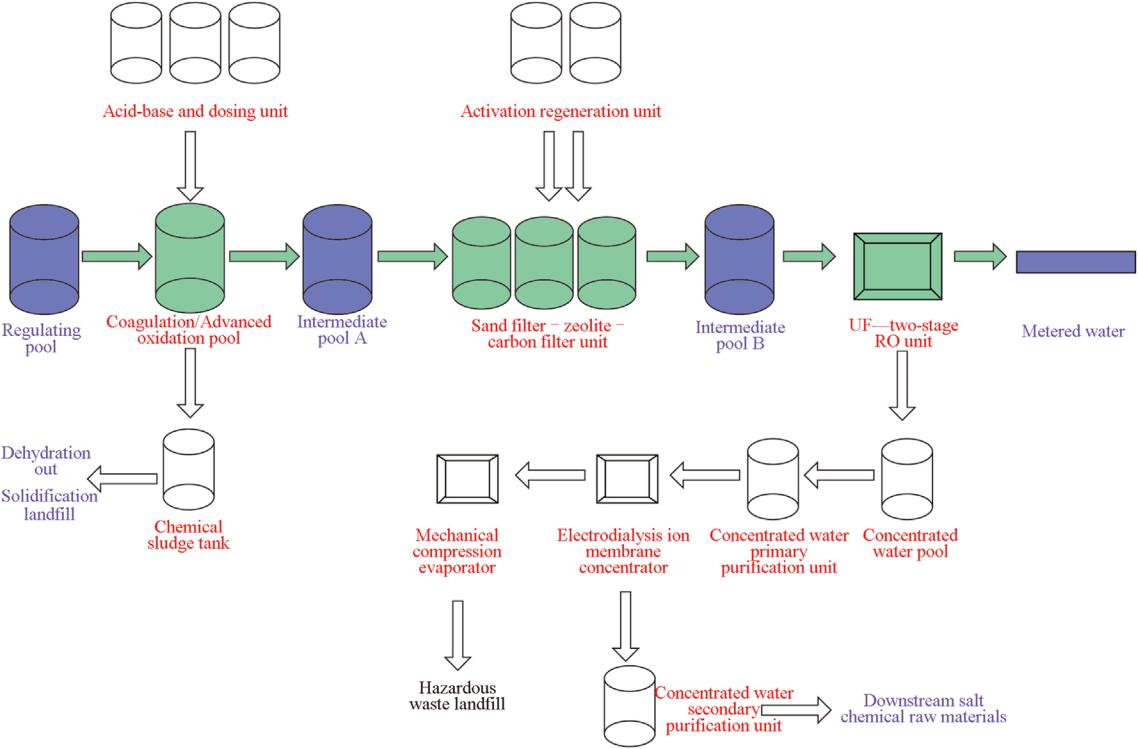


Fig. 4. Process flow for treating produced water in the Fuling Shale Gas Field.

advanced level, whereas the cost was more than 30% lower than that of similar foreign products.

1. Future prospects and the next direction for tackling key problems

Based on the geological characteristics and resource po-tential of shale gas in the Sichuan Basin, as well as the dis-covery patterns of different types of large gas fields, Sinopec has formulated the 14th Five-Year Plan for shale gas devel-opment. Sinopec will thoroughly implement the directive spirit of vigorously enhancing domestic oil and gas explora-tion and development, practice the concepts of green devel-opment and efficient development, strengthen basic research and key technology research, and tackle key problems in the deep Silurian at 4000e5000 m depth in southern Sichuan and in the normal-pressure Silurian in the complex structural belt, to achieve commercial breakthroughs in multiple types of shale gas. In terms of exploration, one trillion cubic meters of reserves in Fuling will be cultivated, and in terms of devel-opment, enhanced recovery technology for shale gas will be continuously explored, helping to realize production stabili-zation and increment with a scale of ten billion cubic meters of shale gas in the Fuling Demonstration Area [[35](#page1)e[40](#page1)].

5.1. Accelerating the development of deep shale gas with normal pressure

The Fuling Shale Gas Demonstration Area has achieved efficient development of shallow over-pressured shale gas

reservoirs with depths shallower than 3500 m, and effective development of shale gas reservoirs with depths ranging from 3500 m to 4000 m. However, deep shale reservoirs are deeply buried, high in construction pressure, and restricted in con-struction displacement, and thus require more fracturing technology and equipment for long horizontal wells. At pre-sent, the enrichment and preservation mechanism and the evaluation technology system of shale gas reservoirs with normal pressure are still unclear, and the low-cost, high-speed drilling technology and high-efficiency fracturing technology in areas with normal pressure have not yet been matched. In the future, with the existing technical systems, workers of the Fuling Shale Gas Demonstration Area will continue to opti-mize and tackle key problems, establish key technologies for shale gas reservoirs deeper than 4000 m and at normal pres-sure, and create a regionally distinguished development model.

5.2. Continuously tackling key enhanced recovery technologies for shale gas

After well pattern infilling and development adjustment in the Jiaoshiba block, the recovery rate was increased from 12.6% to 23.3%, and the recovery rate in the stacked devel-opment and adjustment area reached 39.2%. However, for the Jiangdong and Pingqiao complex structural areas and the Baima deep new area, the potential of development and adjustment and the effect of implementation still must be verified. Therefore, for the next step, Fuling Shale Gas Demonstration Area workers should actively research tech-nology integrating geology simulation and numerical

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| --- | --- |
| X Guo et al. / Natural Gas Industry B 10 (2023) 62e72 | 71 |

simulation, and perform studies focused on reserve production evaluation, integrating geological and numerical simulation based on the coupling of natural fractures and artificial frac-tures in shale gas reservoirs, on efficient volume fracturing of complex fracture networks with a complex stress field, and on the 3D development of enhanced recovery technology under complex mountainous conditions, so as to achieve full utili-zation of shale gas resources.

5.3. Actively promoting new technologies and methods on site

With the application trend of artificial intelligence and big data, the technical system and equipment should continue to be optimized for efficient development of demonstration areas.

① The theoretical research on shale gas reservoir geology and gas reservoir engineering should be strengthened, and the mechanism and production law of gas reservoirs should be further explored. ② The bottleneck of engineering technology should be broken through, and the speed, quality, and cost of drilling, testing, and surface engineering should be improved; in addition, the development and adjustment process system should be continuously improved. ③ The identification of “sweet spots” and the single-well productivity of gas reser-voirs should continue to be improved, production costs reduced, and gas field production increased.

5.4. Strengthening the construction of a green shale gas demonstration area

The economic model of reduction, reuse and recycling should be followed. Through reuse of wastewater, reduction of waste gas emission, and treatment of waste residues, clean production is promoted in the entire process of exploration and development, for purpose of energy conservation, consump-tion reduction, pollution mitigation, and efficiency enhance-ment, so as to practically guarantee both resource development and environmental protection.

6. Conclusions

In the Fuling National Shale Gas Demonstration Area, the construction process has gone through three stages: the exploration and evaluation stage, phases I and II of the con-struction stage, and the stacked development and adjustment stage. Cumulatively, the gas production has exceeded

1. 108 m3, and the area has become the main force for the growth of domestic shale gas production.

During construction of the Fuling National Shale Gas Demonstration Area, the binary enrichment theory for marine shale gas and engineering theory for efficient development of gas reservoirs were established, and four major supporting technology systems were innovated and developed: optimal and fast drilling technology for shale gas cluster horizontal

well groups, distinguished fracture network fracturing tech-nology for shale reservoirs with different geological condi-tions, high-efficiency shale gas collection and transportation technology, and green development technology for shale gas in karst mountainous areas. Thus, the localization of key equip-ment and supporting tools was successfully realized.

For the next step, Fuling National Shale Gas Demonstration Area workers will continue to tackle exploration and devel-opment technologies for deep shale gas with normal pressure. In terms of exploration, one trillion cubic meters of reserves in the Fuling area will be cultivated, and in terms of develop-ment, enhanced recovery technology for shale gas will be continuously explored, which will help to realize production stabilization and increment at a scale of ten billion cubic meters of shale gas.

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Conflict of interest

The authors declare no conflict of interest.

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