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**Shale oil and gas exploitation in China: Technical comparison with US and development suggestions**



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**Abstract:** The shale oil and gas exploitation in China is technically benchmarked with the United States in terms of develop-ment philosophy, reservoir stimulation treatment, fracturing parameters, fracturing equipment and materials, oil/gas produc-tion technology, and data/achievements sharing. It is recognized that the shale oil and gas exploitation in China is weak in seven aspects: understanding of flow regimes, producing of oil/gas reserves, monitoring of complex fractures, repeated stimu-lation technology, oil/gas production technology, casing deformation prevention technology, and wellbore maintenance tech-nology. Combined with the geological and engineering factors of shale oil and gas in China, the development suggestions of four projects are proposed from the macro- and micro-perspective, namely, basic innovation project, exploitation technology project, oil/gas production stabilization project, and supporting efficiency-improvement project, so as to promote the rapid, ef-ficient, stable, green and extensive development of shale oil and gas industry chain and innovation chain and ultimately achieve the goal of “oil volume stabilizing and gas volume increasing”.

**Key words:** shale oil and gas; reservoir stimulation; oil/gas production technology; oil/gas development philosophy; reservoir stimulation treatment; flow regime

**Introduction**

As conventional oil and gas resources increasingly de-plete, unconventional low-grade resources such as shale oil and gas have become a popular field for exploration and development at home and abroad. The United States has taken the lead in accomplishing the shale oil and gas revolution, realizing the large-scale productivity con-struction of shale oil and gas resources [1]. Statistics show that the crude oil output in the United States in 2021 is 5.49×108 t, of which shale oil is 3.62×108 t, accounting for 65.9%; natural gas output is 9736×108 m3, of which shale gas is 7643×108 m3, accounting for 78.5% [2]. Drawing on the successful development experiences of shale oil and gas in the United States, China has also set off a boom in shale oil and gas exploration and development. Statistics show that by the end of 2021, China National Petroleum Corporation (hereinafter referred to as CNPC) had a total of 13.05×108 t of proved shale oil geological reserves and 1.70×1012 m3 of proved shale gas geological reserves. 2021

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saw the peak of CNPC's shale oil and gas production, in which annual shale oil output was 257×104 t, accounting for 2.5% of total crude oil production; annual shale gas output was 128.7×108 m3, accounting for 9.3% of the total natural gas production [3]. Shale oil and gas is gradually becoming an important replacement resource for con-ventional oil and gas at home and abroad [4–5].

This paper systematically summarizes the shortcom-ings of China's shale oil and gas resources development in seven aspects, such as the understanding of flow re-gime and the utilization of oil and gas reserves, by com-paring the technical progress of China and the United States in six aspects of shale oil and gas reservoir stimu-lation, and oil and gas production. It finally puts forward four development suggestions, such as the construction of basic innovation project and exploitation technology project, from the macro to micro perspective, so as to promote large-scale productivity construction and benefit development of shale oil and gas.

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1. **Benchmarking analysis of Sino-US shale oil and gas exploitation technologies**

By comparing the technical progress of China and the United States in terms of shale oil and gas development philosophy, reservoir stimulation strategy, fracturing construction parameters, fracturing equipment and ma-terials, oil and gas production technology, and data/ achievements sharing, the following six gaps are pre-sented.

**1.1. Gap in oil and gas development philosophy**

The differences between Chinese and American shale oil and gas development philosophy are mainly shown in the following four aspects. (1) The understanding of geo-logical evaluation. The United States has transitioned from the traditional single-layer single-phase adsorption theory to the multi-layer multi-phase competitive ad-sorption theory by finely characterizing shale micro- and nano-pores, specific surface and organic pore contribu-tion, thus resulting in a two- to three-fold increase in resources [6–7]. In contrast, China has yet to conduct in-depth research on the production capacity contribu-tion of micro- and nano-pore throats. (2) Practice on sublayer potential tapping. The United States has re-peatedly increased the reserve contribution rate of verti-cal sublayers by fracturing interlayers, while China's sublayer fracturing tests need to be strengthened. (3) Engineering technology. The United States has developed a three-dimensional development and multi-layer utiliza-tion model, and ultra-long horizontal well technology, while China is developing high-density completion tech-nologies, such as small well spacing and dense cutting. Their stimulation mechanisms are different. (4) Exploita-tion philosophy. The United States has established a

concept of full-life cycle energy maintenance, which con-verts formation energy into power, driving oil and gas to flow, so as to enhance oil and gas recovery. In China, however, such philosophy has not been systematically developed, and fine managed-pressure production tech-nology has not been effectively developed yet. There is a large difference in the total amount of shale oil and gas resources between China and the United States. Statistics show that China's shale oil and gas resources are 52% and 66% of those of the United States, respectively. In addi-tion, the difference in shale oil and gas development philosophy between the two countries has led to a sig-nificant gap in the utilization degree of shale oil and gas resources between China and the United States [8–9]. In recent years, adopting a more mature development con-cept, the United States has significantly increased its geologic resource abundance (about 17.4 times that of China), well-controlled recoverable reserve abundance (about 6.25 times that of China), and single-well pre-dicted ultimate recoverable reserves (about 6.25 times that of China).

**1.2. Gap in reservoir stimulation strategy**

The geological characteristics of shale oil and gas res-ervoirs in China and the United States differ greatly (Ta-ble 1 and Table 2). Accordingly, the stimulation counter-measures are obviously different as well, mainly in terms of the length of horizontal well sections for shale oil and gas stimulation, the number of three-dimensional stimu-lation layers and the stimulation methods.

For shale oil, the U.S. shale oil reservoirs are mostly marine deposits with high pressure coefficients, con-tinuous distribution in wide range and thick single layers, so multi-layer three-dimensional fracturing has become a

**Table 1. Comparison of geological parameters of typical shale oil blocks between China and the United States**

|  |
| --- |
| Shale oil Typ |

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Block/ | Hydrocarbon- | Stratigraphic | Sedimentary | Burial | Single- | No. of | TOC/ | Ro/% | Poros- | Pressure | Crude oil |  |
| layer thick- | viscosity/ |  |
| Basin | bearing layer | age | environment | depth/m | ness/m | layers | % |  | ity/% | coefficient | (mPa s) |  |
|  |  | Devonian– |  |  |  |  |  |  |  |  |
| Williston | Bakken Fm. | Marine | 2591–3200 | 15–25 | 3 | 8–20 | 0.6–1.0 | 5–13 | 1.6–1.8 | 0.45 |  |
| Carboniferous |  |
| Permian Wolfcamp Fm. | | Permian | Marine | 1200–3000 | 300–600 | 8 | 2–9 | 0.7–1.0 | 4–12 | 1.0–1.2 | 0.50 |  |
| Ordos | Yanchang | Triassic | Lacustrine | 1600–2200 | 2–26 | 5 | 2–20 | 0.6–1.2 | 4–12 | 0.7–0.8 | 3.00– |  |
| Fm. | 8.00 |  |
|  |  |  |  |  |  |  |  |  |  |  |
| Junggar Lucaogou Fm. | | Permian | Lacustrine | 2340–4500 | 0.5–5.0 | 6 | 1–20 | 0.6–1.3 | 4–12 | 1.0–1.1 | 50.30– |  |
| 123.20 |  |
|  |  |  |  |  |  |  |  |  |  |  |  |

**Table 2. Comparison of geological parameters of typical shale gas blocks between China and the United States**

|  |
| --- |
| Shale gas Typ |

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Block/ | Hydrocarbon- | Stratigraphic | Sedimentary | Burial | Single- | No. of | TOC/% | Ro/% | Poros- Pressure | | Stress |  |
| layer thick- | difference/ |  |
| Basin | bearing layer | age | environment | depth/m | ness/m | layers |  |  | ity/% | coefficient | MPa |  |
| Hayne- | Haynesvile |  | Deep-water |  |  |  | 1.80– | 8.0– | 1.60– |  |
| Jurassic | 3350–4270 | 61–107 | 5 | 0.4–4.0 | 4 |  |
| svile | Fm. |  | shelf |  |  |  |  | 2.50 | 9.0 | 2.00 |  |  |
| Barnett | Barnett Fm. | Carboniferous | Deep-water | 1980–2591 | 30–180 | 4 | 4.0–5.0 | 0.80– | 4.0– | 0.90– | 10 |  |
|  |  |  | shelf |  |  |  |  | 1.40 | 5.0 | 1.20 |  |  |
| Fuling, | Wufeng Fm.– | Ordovician– | Deep-water | 2000–4000 | 20–40 | 5 | 2.0–8.0 | 2.65 | 1.2– | 1.55 | 18 |  |
| Sichuan | Longmaxi Fm. | Silurian | shelf |  |  |  |  |  | 8.1 |  |  |  |
| Southern | Wufeng Fm.– | Ordovician– | Deep-water | 3000–4500 | 50–83 | 8 | 2.5–8.5 | 2.50– | 2.0– | 1.20– | 15 |  |
| Sichuan | Longmaxi Fm. | Silurian | shelf |  |  |  |  | 3.80 | 12.0 | 2.10 |  |  |

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highly-efficient stimulation technology to fully sweep the reserves in longitudinal direction. The current U.S. shale oil can be utilized in three to five layers in three dimen-sions, with horizontal sections up to 2500–3800 m in length. In contrast, Chinese shale oil reservoirs are mostly lacustrine deposits with low pressure coefficient, high crude oil viscosity, low fluidity and small single-layer thickness, so there is a gap in the degree of three-dimen-sional utilization between Chinese and the U.S. shale oil. At present, China's shale oil is mostly utilized in one to two layers, with a maximum of 31 wells in three layers (Platform Hua 100); the stimulated horizontal well sec-tion is mostly 1500 m to 2500 m in length, and there is a gap in reserve control with the United States [10].

As for shale gas, the plane distribution of the sand body in the United States is stable and the horizontal stress difference is small, which makes it easy to form a fracture network structure after hydraulic fracturing and is conducive to the application of production enhance-ment and stimulation technology by long horizontal well sections. Currently the U.S. shale gas horizontal well sec-tions are 2300 m to 4300 m in length, with the longest being up to 6339.8 m (Well Mercury B 5H). In China, however, shale gas reservoirs are buried deeply, the thermal evolution degree of organic matter is high, and sand bodies are highly heterogeneous in the plane, with a large difference in bidirectional horizontal stress, so it is not easy to form a fracture network structure and the construction length of horizontal well section is limited after implementing horizontal well staged fracturing

stimulation [11]. The current horizontal well section is mostly 1200 m to 2300 m long, with the longest being 3166 m (Ning 209H71-2). In addition, the U.S. shale gas reservoirs are thick in single layers, so three-dimensional fracturing technology is mostly adopted to achieve multi-layer utilization in longitudinal direction. Currently, the United States can realize three-dimensional utiliza-tion of shale gas in 3 to 5 layers, with a maximum of 51 wells in 8 layers (CRU-CD2).

**1.3. Gap in fracturing construction parameters**

In recent years, both China and the United States have developed the main stimulation technology of “horizontal well completion + multi-cluster perforation + slick water carrying sand + quartz sand support + multi-stage frac-turing + fracture monitoring” [12]. The comparison of the construction parameters of horizontal wells in typical shale oil and gas blocks between China and the United States (Table 3 and Table 4) show that, for engineering effects, compared with China, shale oil/gas horizontal wells in the United States generally have longer well sec-tions, smaller cluster spacing, and more fractures and higher fracture density. For operation consumption, compared with the United States, China has significantly higher single-fracture sand ratio and construction dis-placement in horizontal shale oil and gas wells. In addi-tion, despite small difference in construction displace-ment between shale oil and shale gas horizontal wells in both countries, the single-fracture sand ratio of shale oil horizontal wells is significantly higher than that of shale

**Table 3. Comparison of horizontal-well construction parameters of typical shale oil blocks between China and the United**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **States** |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  | |  |  |  |  |  |  |  |  |  |  |  |
|  | Length of Length of | | Cluster | Number of | Number | Fracture |  | Single- | Single- | Construction | Sanding | Fracturing |  |
| Block | horizontal | fractured | spacing/ | clusters in | of frac- | density/ | −1 | fracture | fracture | displace- | intensity/ | fluid |  |
|  | section/ | section/ | m | a single | tures |  | sand | sand | ment/ | −1 | intensity/ |  |
|  | m | m | section | (fractures km | ) | ratio/% | content/t | (m3 min−1) | (t m ) | (m3 m−1) |  |
| Permian | 2500– | 45–75 | 4–6 | 6–12 | 410–650 | 164–186 |  | 6.7 | 18.3–18.8 | 12–14 | 3.0–3.5 | 20–25 |  |
| Basin | 3500 |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
| Chang 7 | 1500– |  |  |  |  |  |  | 12.0– |  |  |  |  |  |
| Member, | 45–70 | 8–10 | 4–10 | 120–225 | 80–125 |  | 36.0–37.5 | 12–14 | 3.0–4.5 | 20–25 |  |
| Ordos | 1800 |  |  |  |  |  |  | 15.0 |  |  |  |  |  |
| Jimsar, | 1500– | 45–60 | 6–8 | 6–8 | 204–320 | 136–160 |  | 8.6– | 22.0–37.5 | 14–16 | 3.0–6.0 | 25–30 |  |
| Xinjiang | 2000 |  | 11.5 |  |
|  |  |  |  |  |  |  |  |  |  |  |
| Gulong, | 1600– | 50–70 | 6–8 | 7–10 | 190–340 | 118–136 |  | 10.0– |  | 12–16 | 3.5–4.5 | 21–28 |  |
| Daqing | 2500 |  | 11.0 |  |  |
|  |  |  |  |  |  |  |  |  |  |  |



**Table 4. Comparison of horizontal-well construction parameters of typical shale gas blocks between China and the United States**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Length of | Length of | Cluster | Number | Number | Fracture |  | Single- Single- Construction | | | Sanding | Fractur- |  |
|  | of clus- |  |  |
| Block | horizontal | fractured | spacing/ | ters in a | of frac- | density/ |  | fracture | fracture | displace- | intensity/ | ing fluid |  |
|  | section/ | section/ | m | single | tures | −1 | | sand | sand | ment/ | −1 | intensity/ |  |
|  | m | m | (fractures km | ) | ratio/% | content/t | (m3 min−1) | (t m ) | (m3 m−1) |  |
|  |  |  |  | section |  |  |  |  |  |  |  |  |  |
| Haynesvile | 2272–3020 | 40–50 | 5.0–8.0 | 6–9 | 360–540 | 158–178 |  | 6.7 | 28.4–30.7 | 12.0–14.0 | 4.5–5.5 | 35–45 |  |
| Marcellus | 3048–4247 | 31–60 | 4.0–6.0 | 6–10 | 600–750 | 177–196 |  | 6.7 | 13.2–19.8 | 12.0–14.0 | 2.6–3.5 | 22–25 |  |
| Changning, | 1170–2647 | 59–91 | 6.0–11.5 | 6–12 | 120–352 | 100–133 |  | 4.9–8.9 18.5–28.6 | | 15.0–18.0 | 1.9–3.8 | 21–34 |  |
| Sichuan |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Weiyuan, | 1400–2253 | 60–130 | 5.7–16.4 | 3–17 | 73–282 | 52–125 |  | 5.5–8.0 23.1–40.2 | | 12.0–15.3 | 2.1–2.9 | 20–31 |  |
| Sichuan |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  | 946 | |  |  |  |  |  |  |  |

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gas horizontal wells.

**1.4. Gap in fracturing equipment and materials**

1.4.1. Operation and maintenance of fracturing truck unit

China largely keeps pace with the United States in the development and application of fracturing trucks. Diesel fracturing trucks are gradually phased out, electric-driven fracturing trucks become the mainstream, and gas frac-turing trucks become substitutes. In the United States, diesel fracturing trucks are mainly Type 2500 and elec-tric-driven fracturing trucks are mainly Type 7000. The core components of China’s diesel fracturing truck units, such as engine, gearbox and chassis still rely on imports, but the degree of localization of Type 7000 electric-driven fracturing trucks is relatively high.

There is a big gap between China and the United States in metering, diverting and equipment control of fractur-ing blender trucks [13]. The United States has realized ac-curate metering and intelligent diversion, which can co-ordinately control multiple equipments for testing, sand mixing, blending and other operations; China prelimi-narily has the control capacity of constant pressure and constant displacement, but it is still dominated by man-ual control, and the operation of each device is relatively independent.

In addition, the United States has realized the dual well synchronous zipper-fracturing, with rapid development of information and intelligent technology, closed-loop fracturing control and one-touch operation capability, and can control cooperative operation of 60 pump trucks. In China, however, the single well zipper-fracturing is mainly adopted, and the maintenance of truck units is mainly based on empirical data, so the automatic opera-tion capability needs to be strengthened [14–15].

1.4.2. Application and operational efficiency of packing tools

In addition to the environment, feed flow, sand han-dling, casing deformation, casing damage, to name a few, the selection of packing tools has a great impact on frac-turing efficiency [16]. In the United States, staged fractur-ing is dominated by fast-drilling bridge-plug tools, and staged fracturing in shale oil and gas platforms can reach 6–8 stages/d; China mainly uses dissolvable staged frac-turing tools, and the staged fracturing of shale oil and gas platforms can reach 1–2 stages/d. Similarities and differ-ences of packing tools in China and the United States include: (1) There is a big difference in pumping and drilling speed in fast-drilling bridge plug between China and the United States. The U.S. bridge plug can be pumped at the speed of 250 m/min, and the drilling speed has been increased from 30 min/piece in 2012 to 4 min/piece in 2019; the pump speed of the China’s bridge

plug can reach 80 m/min, and the drilling speed can be 15–30 min/piece. (2) The bearing capacity and applicable temperature of the dissolvable bridge plug/ball seat is not much different in China and the United States. The dis-solvable ball seat of Infinity in the United States can bear the pressure of 70 MPa and has the temperature resis-tance of 24–177 C; the dissolvable metal bridge plug in China can bear the pressure of 80 MPa and has the tem-perature resistance of 20–180 C, while the rubber sleeve bridge plug can bear the pressure of 70 MPa and has the temperature resistance of 40–150 C. (3) The delay mechanism of toe sliding sleeve is different. The liquid throttling mechanism is adopted in the United States. The highest casing pressure is 140 MPa, the highest tem-perature is 180 C, the rupture pressure of the rupture disk is 85–105 MPa, and the delay opening time of the sliding sleeve is 35–60 min. The dissolvable delay mechanism is adopted in China. The highest casing pressure is 140 MPa, the highest temperature is 150 C, the rupture pressure of the rupture disk is 85–105 MPa, and the delay opening time of the sliding sleeve is 15–60 min.

1.4.3. Targeted design and process control of fracturing fluid

Low viscosity slickwater has been widely used at home and abroad. Its main effect is to reduce drag and generate fracture network. The drag reduction performance of slickwater in China and the United States is not much different, with the drag reduction rate reaching 70%, but there are significant differences in terms of application degree, targeted design and process quality control [17–18].

1. In application degree: the slickwater applications in U.S. shale oil and gas account for more than 90%, whereas the application ratio of slickwater in south Si-chuan shale gas is more than 95%, that in Changqing shale oil is nearly 100%, and that in Xinjiang Jimsar shale oil is only 52%. (2) In targeted design: in the United

States, it is prepared with clean water, and the viscosity of slickwater is less than 9 mPa s. The formula system suit-able for different blocks and different degrees of miner-

alization has been formed. The main component of China’s high viscosity slickwater (30–50 mPa s) is resis-tance reducing agent, and the application of functional and targeted formula is less. (3) In process quality control: liquid additive operation in the United States uses te-lemetry systems that provide construction locations via satellite links to monitor addition rates and concentra-tions at any time and place for real-time automated tracking, adjustment, and pre-warning. China still uses traditional metering pumps and other mechanized me-tering methods.

1.4.4. Application level of quartz sand proppants

The United States adheres to the concept of “localiza-

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tion of sand source”. From 2011 to 2021, the amount of proppant consumption in the United States increased from 1820×104 t to 8600×104 t, with quartz sand ac-counting for more than 98% of the total. The proportion of quartz sand in proppant in the Haynesville deep shale gas is over 95%, and 0.380/0.212 mm (40/70 mesh) and 0.212/0.109 mm (70/140 mesh) are the main particle sizes. In addition, the application scale of 0.074 mm (200 mesh) quartz sand is gradually increasing, and related tests have also been carried out for 0.048 mm (300 mesh) quartz sand. Compared with the United States, there is a gap in the application scale of quartz sand and the ap-plication of small particle size quartz sand in China [19]. In CNPC, for example, the amount of proppant consumption increased from 130×104 t in 2014 to 440×104 t in 2021, and the proportion of quartz sand increased from 45% to 87%. The proportion of quartz sand applied to the shale gas at the depth of less than 3500 m increased from 34% to 72%, and that at the depth of more than 3500 m reached 47%, while the proportion of quartz sand applied to shale oil reached almost 100%. The proppant for shale gas in the Sichuan Basin is mainly quartz sand with 0.212/0.109 mm (70/140 mesh), accounting for 70%; for Changqing shale oil, 0.212/0.109 mm (70/140 mesh) and 0.212/0.109 mm (70/140 mesh) quartz sand are mixed in a specific ratio.

**1.5. Gap in oil and gas production technology**

In oil production technology, shale oil horizontal wells in the United States mainly use wide-range electric pump lift and gas lift. The maximum pump depth can reach 3700 m, and the distance between the pump setting and the horizontal interval (also called pump-hole distance) is 100–300 m. The average cycle of pump inspection is about 600 d. Shale oil horizontal wells in China are mainly lifted by rod pump and electric submersible screw pump. The maximum pump depth is only 2500 m, and the distance between the pump setting and the horizontal interval is 600–1000 m, so the depth and production po-tentials are still large. The average cycle of pump inspec-tion in China is only 65% of that in the United States, but the operation frequency is about 54% higher than that in the North America [9].

In gas production technology, the United States has developed the concept of full-life cycle formation energy maintenance and the corresponding gas production technology system. The controlled pressure production can be fine to 0.01 MPa/d, the capacity of operation under pressure can reach 105 MPa, drainage and gas production in different production stages has been serialized, and the predicted final recoverable reserves of a single well can be increased by 30%–40%. The concept of formation en-ergy maintenance has not been developed systematically in China, and the precise managed-pressure production technology has not been effectively formed [20]. The oper-ating pressure of tubing running under the maximum

pressure is only 35 MPa, which cannot support direct tubing running for production after fracturing. The drainage and gas production technology in the early stage of production in China is quite different from that in the United States.

**1.6. Gap in data/achievements sharing**

In historical data, FracFocus, Drillinginfo and other databases have been built up in the United States, and more than 100 000 hydraulic fracturing reports of 27 states have been published, covering more than 300 types of fluids, proppants and other well materials in 10 cate-gories, including chemical composition, content, concen-tration, toxicity and harmful evaluation information. Therefore the basic data, design scheme, material infor-mation, construction parameters and application tech-nology of fractured wells can be shared. Oil companies in China are building dream cloud and data lake systems. Each oilfield reported basic construction information in a statistical way, but the content is simple and the format is inconsistent. The information system of well materials is still to be planned [21].

As for real-time data, Saudi Aramco, Shell, Baker Hughes, Halliburton and other companies have built up a comprehensive drilling and completion center that inte-grates real-time monitoring, optimization, decision mak-ing and commanding, focusing on the whole process from plan design, tracking and monitoring, real-time optimization to exploration and development, dedicating to achieve the full-life cycle optimization of blocks. China’s oil companies are preparing to build intelligent support centers for engineering operations. Southwest Oil & Gasfield, Xinjiang Oilfield, Changqing Oilfield and other oilfields have remote decision-making and com-manding systems that basically have the capacities of remote monitoring, decision making and commanding, and are crucial to the digital transformation of major oilfields [22].

1. **Shortcomings of Chinese shale oil and gas exploitation technologies**

The comparative analysis of shale oil and gas produc-tion technology between China and the United States clarifies the gap between the two countries, and summa-rizes seven shortcomings in the China’s shale oil and gas development.

**2.1. The understanding of flow regime**

The main task of reservoir development is well layout, and the main task of reservoir stimulation is fracture layout, and the core element of both is to clarify the flow regime of reservoir fluid [23]. Therefore, clarifying the fluid flow regime of shale reservoir can provide theoretical guidance for the optimization of shale oil and gas development plan.

The following weak points remain in the current re-

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search on fluid flow regime: (1) The fluid flow process after shale fracturing involves multi-scale and multi-po-rous medium, which requires consideration of mi-cro-scale molecular motion and matrix diffusion and flow, as well as macro-scale fracture conductivity, interaction between natural and artificial fractures, and interaction between beddings and artificial fractures. Therefore, the flow regime is extremely complex, and relevant basic research needs to be strengthened [24–25]. (2) The rela-tionships between residual oil and gas distribution and well pattern/well spacing, fracture interval, and fracture length need to be verified through field practice [26]. (3) Platform-type development and factory-like operation increase the stress disturbance between wells. Therefore, it is urgent to develop and apply geological-engineering integrated fracturing simulation software considering the fluid-solid-thermal coupling throughout the full-life cycle of oil and gas wells.

**2.2. The production of oil and gas reserves**

Improving the production of shale oil and gas reserves is the premise of increasing the production capacity of a single well [27], so it is necessary to deepen and develop the basic understanding and development technology of improving the producing of shale oil and gas reserves.

The current research on the producing of shale oil and gas reserves has the following weaknesses: (1) The pro-duction capacity contribution of micro- and nano-pore throats is lack of understanding. The proportion of mi-cro- and nano-pore throats in shale is more than 70%. The key technologies for producing reserves from micro-and nano-pore throats with high specific surface area and improving the recovery degree of oil and gas reserve need to be further studied. (2) The recovery ratio of a single well is low and the declining rate is large. The supporting technologies to maximize the producing of shale oil and gas and delay the decline of production are still being explored. (3) The function that fractures control reserves is not given full play, and well spacing, fracture interval and fracture length do not match reservoir size. (4) The three-dimensional development technology has not been fully developed, and the number of vertical production layers and platform wells of shale oil are insufficient. The well type and well spacing design of three-dimensional development need to be optimized, while the experiment of three-dimensional development to improve the pro-duction rate of shale gas needs to be carried out.

**2.3. The monitoring of complex fractures**

Shale reservoirs are characterized by strong heteroge-neity, complex stress characteristics, and developed bed-ding and natural fractures. After fracturing, a complex fracture network with artificial and natural fractures is usually formed, which increases the difficulty of quanti-tative characterization of fracture size [28]. Three-dimen-

sional characterization of fracture network structure is the premise of accurate evaluation of postfrac effect, so it is necessary to develop high-precision fracture monitor-ing technology.

At present, there are still the following weaknesses in fracture monitoring technology: (1) It is difficult to iden-tify fractures quantitatively with microseismic, which is manifested in that stress disturbance and seismic events generated by fractures cannot be distinguished, and it is difficult to make sure whether the microseismic event point is the location of fracture arrival. (2) The clinome-ter cannot accurately characterize the fracture height. Currently, it can only characterize the fracture length and complexity. (3) Distributed optical fiber DTS/DAS (dis-tributed optical fiber temperature testing sys-tem/distributed optical fiber vibration sensing system) cannot evaluate the far-field fractures, but can only re-flect the status of the perforation inflow, so it can hardly reflect the fracture morphology. (4) Controllable source electromagnetic and optical fiber monitoring of the ad-jacent well are not mature enough. Although it can characterize the opening of multiple clusters of fractures and track the distribution of fracturing fluid in the for-mation, the collection accuracy and stability need to be improved, so the fracture height cannot be accurately characterized.

**2.4. The repeated stimulation technology**

The production rates of horizontal shale oil and gas wells usually present dynamic changes in the production process, which will eventually become low-yielding and inefficient wells after long-term stable production. In addition, some horizontal wells are not completely stimulated in the initial stage of development, with large well spacing and cluster spacing, low construction dis-placement, and guanidine gum system as the main frac-turing fluid, which makes the ability of fracture control-ling reservoir not reach the best. Therefore, in order to increase production and develop potential of remaining oil and gas [29], it is necessary to take measures such as repeated stimulation and supporting diagnosis for low-producing and low-efficiency wells and the wells that are not stimulated properly in early stage and suffer frac-ture failure, with lost interval or inaccurate clustering [30].

At present, the repeated stimulation technology of horizontal wells for shale oil and gas still has the follow-ing shortcomings: (1) The dynamic characteristics of production in the development process are complex and it is difficult to accurately diagnose the causes of low production. (2) The law of oil-gas-water three-phase flow is complicated, and it is difficult to accurately character-ize the remaining oil distribution. (3) The spatial and temporal evolution law of stress field is complex, which makes it difficult to optimize refracturing interval and

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timing. (4) The lack of effective packing tools for frac-tured wellbore makes it difficult to reconstruct horizontal wellbore. (5) Given the high geological complexity of the reservoir to be refractured, it is difficult to accurately evaluate the refracturing effect.

**2.5. The oil and gas production technology**

In order to realize the large-scale and highly-efficient development and production of shale oil and gas re-sources, it is necessary to carry out the research and ap-plication of related oil and gas production technology [31]. At present, there are still following weak points in deep shale oil well lifting at the depth more than 2500 m, pre-cise managed-pressure production of shale gas wells, and horizontal well drainage and gas production: (1) The low lifting capacity of shale oil wells is characterized by high wax content and gas-liquid ratio in the produced fluid, and severe off-center wear of the oil production pump, resulting in short pump inspection cycle (42% of that of conventional wells), and the depth of the pumping unit and electric submersible screw pump is less than 2500 m.

1. There is still potential in shale gas energy mainte-nance. At present, the pressure control accuracy of man-ual replacement nozzle is only 1/10 of that of electric nozzle, and the tubing running capacity under pressure is too low to support the tubing running directly after fracturing. A large amount of formation energy is con-sumed in the wellbore drainage, which inhibits the im-provement of the predicted ultimate recoverable reserves of a single well. (3) Horizontal well drainage and gas production is difficult, which shows that wellbore liquid level in 90% of shale gas wells is near the tubing shoe in the middle and late stage of development. The current drainage and production technology cannot clear away the liquid loading in the horizontal section, so that more than 40% of the remaining oil can be hardly produced.

**2.6. The casing deformation prevention technology**

As the exploration and development of shale oil and gas develops to middle and deep intervals, the problem of casing deformation becomes more and more serious [32], making anti-deformation technology of casing an effec-tive means for domestic oil companies to reduce eco-nomic losses and ensure oil and gas production safety.

At present, there are still following weaknesses in cas-ing deformation prevention technology: (1) Deep shale gas wells face severe situations of casing deformation. For example, deep shale gas horizontal wells in Sichuan and Chongqing have serious casing damage, with a casing damage rate of 47.3%. The casing damage mechanism needs further study. (2) Casing deformation prevention technology is still being explored. For complex geological conditions and high-intensity stimulation environment, the adaptation of well completion technology and the

material selection are still being explored. (3) Horizontal well casing deformation prevention technology has not been broken through. Conventional casing shaping technologies for reduced casing in vertical wells, such as explosion, extrusion and milling, as well as casing re-placement in breaking wells, expansion pipe patch tech-nology and other means are not applicable in horizontal wells. Due to the lack of effective wellbore repair methods for casing deformation in horizontal wells, it is urgent to strengthen the research of casing deformation prevention technology [33].

**2.7. The wellbore maintenance technology**

In 2021, CNPC put 18 480 horizontal wells into pro-duction, and shut down 1527 wells (1258 oil wells and 269 gas wells) for more than 180 d due to wellbore failures. Therefore, wellbore maintenance plays a very important role in ensuring shale oil and gas production [34].

At present, there are still following weaknesses in wellbore maintenance operations: (1) It is difficult to accurately describe the operation object, which shows insufficient information from the mark of regulus lead at horizontal section, unintuitive perception of multi-arm caliper and electromagnetic defect detection instrument, and no breakthrough in terms of quantitative analysis of visual images. (2) Water searching, water plugging, and water control technologies are not perfect. High water cut is the main factor for the sharp production decrease and even shut down of horizontal wells. At present, hor-izontal wells in Changqing Oilfield lose 1678 t of daily productivity and 3816×104 t of controlled reserves due to high water cut. (3) Sand production and scaling of hori-zontal wells are serious, and sand flushing and scaling removal are difficult and inefficient. Besides, flushing fluid loss of low-pressure horizontal wells is serious, and sand flushing operations of conventional pipe string in the wells with horizontal section exceeding 2000 m are limited. In 2021, the average sand flushing time of a sin-gle well in Changqing Oilfield is 17.5 d, and the longest time can reach 28 d. The average water consumption of the well is 1271 m³, and the loss rate is 57.1%. (4) Complex breakdown maintenance technology needs to be broken through, which is specifically manifested as the un-matching of complex breakdown maintenance technolo-gies, such as unstuck, fishing and wellbore reconstruction, as well as the difficult operations.

1. **Development directions and suggestions**

In view of the shortcomings of shale oil and gas pro-duction technologies in China, “four major projects” have been proposed from macro and micro perspective to promote the large-scale productivity construction and highly efficient development of shale oil and gas re-

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sources in China.

**3.1. Strengthen the construction of basic innovation projects**

Given the special characteristics of shale oil and gas, strengthening the mesoscopic researches on “hydrocar-bon generation mechanism of organic matter, evolution law of ground stress field, fluid flow regime and proppant transport mechanism”, and optimizing the design of well and fracture layout are extremely important to expand the scale of shale oil and gas and push forward with technological advances. Specific aspects include: (1) Se-lection of sweet spot sections. That is to select sweet spot sections based on organic matter maturity, formation burial depth, reservoir thickness, porosity and perme-ability condition, along with the qualities of hydrocarbon, reservoir, engineering and crude oil. (2) Study on flow regime of pore throats-fracture system. That is to reveal the multi-scale flow regime that fluid flows from micro-and nano-pore throats to hydraulic fracture, and to wellbore after shale reservoir fracturing, and clarify the relation between effective flow volume and production decline, based on three major problems of shale oil (gas), i.e. oil (gas) generation, oil (gas) storage and oil (gas) enrichment, along with theoretical analysis, laboratory study and numerical simulation, so as to provide theo-retical guidance for the co-optimization of well pat-tern/well spacing, stage/cluster spacing and stimulation scale [35]. (3) Basic research on reservoir stimulation. That is to analyze fracture morphology based on the detailed characterization of the mechanical properties of thin interbeds, clarify the evolution law of four-dimensional ground stress field in the reservoir during the full-life cycle, and understand the propagation laws of multiple fractures between wells under the three-dimensional well pattern stimulation mode, and the propagation laws of three-dimensional fractures under the condition of the interaction of centimeter-level multiple beddings, so as to provide theoretical guidance for the target optimization and technology optimization of shale oil and gas. (4) Ba-sic study on oil and gas production. That is to develop the technologies for the lifting and production optimization, flow assurance, and wellbore integrity control of oil and gas wells under complicated well conditions, based on the relationship between the flow mechanism of forma-tion fluid and the wellbore lifting.

**3.2. Strengthen the construction of exploitation technology projects**

Strengthening the construction of shale oil and gas ex-ploitation technology projects involves both construction of stimulation projects, and construction of oil and gas production projects.

For stimulation projects, more efforts should be made at the mesoscopic-level, such as “fracture-controlling

fracturing optimization and design, upgrading of frac-turing software, intellectualization of fracturing equip-ment, improvement of packing tools, improvement of liquid performance, and expansion of quartz sand appli-cation scale”, so as to provide technical support for the stimulation of shale reservoirs. Specifically, this includes the following aspects. (1) Improve the fracture control stimulation technology, and form the optimal well spac-ing and optimal fracture spacing pattern for horizontal wells, so as to realize the maximum utilization of reserves.

1. Improve the performance of FrSmart fracturing soft-ware, strengthen the integrated platform, and improve the scientific nature of fracturing design. (3) Promote the intellectualization of fracturing equipment, develop fracturing blender truck metering and equipment auto-mation controlling, and improve the cooperation level of simultaneous fracturing in two wells. (4) Improve the performance of packing tools, promote the research and development of the drillable bridging plug and screw drill, and improve the supporting process and technology. (5) Improve the performance of fracturing fluid, the adapta-bility of slickwater, and the application ratio. (6) Select proppant materials, carry out application tests of 0.074 mm (200 mesh) quartz sand, and expand the application of quartz sand in reservoir deeper than 3500 m.

In oil and gas production engineering, it is necessary to strengthen the joint development of oil production tech-nology and gas production technology. The development of oil production technology requires the following strategies: (1) Research on the lifting technology for the wells at the depth more than 2500 m, improve the com-prehensive wellbore governance technology, and acceler-ate the intelligent development of digital oil production.

1. Develop the supporting lifting equipment for the wells at the depth more than 2500 m to develop multi-layer platform production technology. (3) Improve the har-nessing techniques of deep deviated well/high gas-liquid ratio/high wax content/off-center wear wellbore, and develop the harnessing techniques of shale oil wellbore.
2. Promote digital metering and intelligent control technology for shale oil platform wells to achieve auto-matic metering and control. The development of gas production technology requires the following strategies:
3. Strengthen technical research and development on shale gas tubing running timing, horizontal interval drainage and gas production, etc. to ensure the ability of gas wells to produce continuously and steadily. (2) Ac-celerate the localization of electric nozzle, tackle key methods of fine pressure control, and prepare the tech-nical specifications of fine pressure control. (3) Improve the full-life cycle energy maintenance technology, im-prove the operation capacity under pressure, and apply jet pump, gas lift and other external forces for efficient liquid drainage, thus improve oil and gas recovery factors.

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1. Tackle technologies such as plugging prevention and liquid loading removal in horizontal tubing shoes to en-sure the sustainable and stable production of shale gas in the middle and late stages.

**3.3. Improve the construction of oil and gas production stabilization projects**

Carrying out diagnostic technology research before fracturing in mature areas, such as “residual oil and gas characterization, ground stress field analysis, previous fracturing evaluation, refractured formation selection, and refracturing timing determination” can provide a theoretical and technical basis for repeated potential tapping of shale oil and gas horizontal wells. In addition, focusing on wellbore reconstruction technologies, such as horizontal well expansion pipe patch technology and small casing cementing technology can provide support for accurate implementation of refracturing [36]. Shale oil and gas production stabilization projects include: (1) Residual oil distribution characterization. Finely re-charac-terize the distribution of residual resource of single sand body, so as to select potential well formation. (2) Stress field simulation analysis, that is, analyzing ground stress field evolution laws via rock mechanics physical model experiment and numerical simulation, so as to optimize the refracturing plan. (3) Well selection and timing for re-fracturing. Analyzing the variation pattern of pressure field and seepage field, and determine well selection conditions and timing for refracturing. (4) Expansion pipe patch technology. Carrying out research on high-strength expansion pipes and horizontal expansion tools and increasing the length of continuous patching. (5) Small casing secondary cementing, that is, strengthening the breakthrough and field test of gel plugging and loss con-trol technology for the large-scale fracture and narrow gap annulus cementing technology to increase production.

In order to ensure long horizontal intervals, the work-over and supporting operation techniques for the hori-zontal wells with long interval (above 1500 m) need to be tackled urgently [37]. Specifically, these include: (1) Visual comprehensive detection technology for horizontal wells, that is, tackling visual comprehensive detection tools and supporting operation technology, and solving the prob-lem of accurate description of workover objects. (2) Wellbore cleaning technology of low pressure and long horizontal wells. Tackling the key sand flushing operation technology for horizontal wells with long horizontal sec-tion and low-pressure circulation loss, and improve the wellbore cleaning ability. (3) Electric cutting unfreezing and fishing technology. Improving the efficient electric cutting tools, and upgrading unfreezing and fishing tools of horizontal wells.

**3.4.** **Promote supporting efficiency-improvement projects**

Efforts should be made to build up the "FracFocus"

platform with Chinese characteristics, and empower arti-ficial intelligence to multiple links of reservoir informa-tion and outflow status, perforation information and downhole tool status, tubing and casing information and wellbore lift status, and downhole material information and operation status, through the Internet of Things, to build a new pattern of intelligent production technology system. Efforts in digitization and information construc-tion of reservoir, wellbore and surface can help improve the quality and efficiency of shale oil and gas develop-ment [38]. To facilitate the digital transformation of pro-duction technologies, the following measures are neces-sary. (1) Digital transformation and intelligent develop-ment of reservoir stimulation, that is, accelerating the construction of remote decision-making center in China, promoting resource sharing, gradually realizing the Internet of Things (IoT) control of each stage of fractur-ing, and building a system that can conduct intelligent reservoir stimulation design and implement decision making. (2) Intelligent development of oil production technology. Control the outflow of oil, wellbore lifting, production on the surface, digital metering, etc. via the IoT, so as to develop intelligent oil production technology.

1. Development of intelligent gas well diagnosis tech-nology for gas production, to evaluate the working con-ditions, such as wellbore flow in gas reservoirs, liquid loading and gas collection on the surface.
2. **Conclusions**

Shale reservoirs are more difficult to develop because of their harsher geological and engineering factors than those of conventional reservoirs. Inspired by the shale oil and gas revolution in the United States, after years of development, China has built up a horizontal well “dense cutting” fracturing technology system that can basically meet the demand of “fracture-controlled reserves” of shale reservoirs, providing technical support for the effi-cient development of shale oil and gas fields in Sichuan and Chongqing region, Ordos Basin, Songliao Basin, etc. However, there is still a big gap between China and the United States in reservoir stimulation and production technology of shale oil and gas. Therefore, it is necessary to deepen the understanding of basic laws, tackle the “bottleneck” technology of oil and gas stimulation, carry out on-site fracturing and production tests, and develop the technologies supporting oil and gas development. At the same time, efforts should be made to strengthen the construction of innovation projects, promote the digital transformation of production technology, and build a new pattern of intelligent development. This is of great significance to promote the rapid, efficient, stable, green and scale development of shale oil and gas industry chain and innovation chain, so as to achieve the goal of “oil volume stabilizing and gas volume increasing”.

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