Current application situation and developments of low-cost sand proppant in China

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Abstract. Since 2014, the petroleum companies in North America have adopted self-operated and self-supplying modes to cut costs for proppants, such as replacing ceramic with sand and building sand plants nearby, achieving win-win results of continuous growth in oil and gas production and economic benefits. Enlightened by such situation in North America, in this study, the feasibility of sand promotion is demonstrated systematically in terms of the basic theoretical research, experimental testing and field tests. The research results indicate that: (1) the sand currently used in China can completely meet unconventional reconstruction requirements, as it has a crushing resistance grade equivalent to that of the yellow sand from the U.S. and the crushing rate and flow conductivity basically close to those of such yellow sand; (2) based on the characteristics of unconventional petroleum reservoirs and fluids and the differences between their completion modes and those of conventional petroleum reservoirs, the beneficial development of unconventional petroleum that can be realized by increasing the laying concentration and using the sand with small particle sizes has been verified; (3) the development potential of Shixi, Jiangyou, Yiliang and Chuxiong is demonstrated by conducting the localization feasibility study of sand sources to lay the foundations of further cost cutting and efficiency enhancement for unconventional petroleum; (4) the field tests have indicated that, in China, the sand used for fracturing can fully meet the technical demands of the reconstruction for unconventional reservoirs not deeper than 3,500 m and shows good production effect and economic efficiency. In view of these research and understanding, the cost cutting of sand for more benefits shall be further enhanced to ensure the low-cost petroleum development in China. Specifically, the promotion and application of sand and building sand plants nearby shall be strengthened.

1. Introduction

Hydraulic fracturing, the main technical approach or increasing the production of a single well and the recovery ratio of unconventional petroleum, provides a technical guarantee for the efficient development of oil and gas fields [1]. After fracturing, the fracturing fluid is gradually discharged, and only the proppant supporting fractures in the reservoir is left. In this way, a path with high flow conductivity is provided and thus increases the hydrocarbon flowing into the wellbore to keep the long-term smoothness of hydrocarbon seepage paths [2]. This relationship highlights the considerable significance and key role of the proppant and its selection in hydraulic fracturing operation. The costs on proppants account for the main part of the initial production costs of oil and gas wells and
determine the economic life of these wells [3]. Excessive proppant costs will be unnecessarily wasteful; whereas, if the investment is too low, oil and gas wells will return no economic benefits due to the insufficient fluid production of the reservoir. Accordingly, the ultimate goal of hydraulic fracturing design is to minimize the costs and maximize the reservoir productivity, and thus the selection of proppant types and particle sizes is crucial [4].

At present, there is a huge gap between the consumption of sand in China and that in U.S. [5-9]. In 2015, the consumption of petroleum proppants in China was only 1.44 million tons, with sand consumption accounting for 46%, and the large particles proppant of 20/40-mesh and 30/50-mesh sizes were dominant. From 2011 to 2015, in the PetroChina Changning-Wei yuan national shale gas demonstration zone, 70/140-mesh sand and 40/70-mesh ceramic were mainly used, with sand accounting for only 10%~20% [10]. The sand fracturing strength of horizontal wells in Mahu Area of Xinjiang Uygur Autonomous Region was 1.0-2.0 m³/m, and the amount of sand in a single well was 1,800~2,700 m³. The proppant costs account for about 10% of well construction costs (5.35 million yuan on average), resulting in a high burden of costs. Based on the proppant consumption of 5~6 million ton/year, if ceramic can be fully replaced with sand, the annually reduced costs can reach as high as 3.5-5.2 billion yuan, which indicates considerable space of cost reduction. Therefore, low-cost development is the only way for unconventional reservoir. In the light of the characteristics and status of unconventional reservoir development in China, it is of significantly practical importance to actively explore the technical applicability of sand and carry out mine site tests.

This paper systematically sorted out the development and change trends of fracturing proppants in North America in recent years, clarified the new progress of reservoir reform proppants at home and abroad, and summarized the gaps between domestic and foreign reservoir reform proppant use concepts. On this basis, combining the characteristics of China's unconventional reservoir development and the current situation, the quality of sand in China's six major sand sources was evaluated, basic theoretical research on the feasibility of sand application was carried out, and the localization of sand sources in China was excavated. The potential of the final demonstration of the effectiveness and economics of the promotion and production of sand in key oil and gas blocks. It will improve the quality and efficiency of unconventional oil and gas under the current low oil price, it is of great significance to development of gas industry.

2. Level of sand technical in China

The abundant natural sand proppant resources are formed through the migration by wind from west to east. The sand mainly distributed in Luliang Oilfield of Xinjiang Uygur Autonomous Region, Anning District of Lanzhou city (Gansu Province), Qingtongxia city of Ningxia Province, Weichang of Chengde City (Hebei Province), Chifeng City and Tongliao City of Inner Mongolia, etc. The average particle size of crude sand changes regularly with contributing factors; the longer the moving distance, the smaller the average particle size is. The crushing rate shows a gradual decline trend, while sand quality is getting better. Main particles in crude sand are of 20/40-mesh, 30/50-mesh, 40/70-mesh and 70/140-mesh sizes, and the sand particles with 20-mesh or larger sizes are relatively rare. The sand source areas of Weichang, Chifeng and Tongliao are dominated by medium-grained and fine-grained crude sand, making them the current main production bases of 40/70-mesh and 70/140-mesh fracturing sand in oil and gas fields. The compositions of crude sand are different depending on different regions, with sand accounting for the largest part, i.e. over 80%. The is grey white or light white, translucent and semi-rounded and has glassy luster and high hardness. Other impurities in crude sand are potassium feldspar, plagioclase, flint, magnetite, garnet and zircon. In the sand source area of Luliang, the iron content is high, and thus there are many black particles, affecting the quality of sand. In the sand source areas of Lanzhou and Qingtongxia, crude sand contains much mud (about 50%), resulting in low sand production and high production costs; however, as these areas are close to the Changqing Oilfield and Yanchang Oilfield, the transportation costs are low. In the sand source area of Chifeng, a small amount of sand is white and has high purity, with the indexes approximate to the white sand in the U.S.
As the performance of the sand from different mining locations in the same sand source area fluctuates greatly, actual sample testing data must be used for design and field application, and using manual data singly is unacceptable. The processing of sand includes claiming mining rights (locations and permits), mining (stripping, blasting and crushing), wet processing (cleaning), drying, screening, testing and delivery from plants. Inadequate processing may lead to dirty materials, material agglomerating and poor screening. Once the mineral composition and crystal structure of the sand are confirmed, controlling the particle size distribution of finished sand and sand surface treatment becomes the key for improving the quality of natural sand proppants. Unlike ceramic proppants, the particle size of sand depends on the natural particle size distribution of crude sand.

The properties of the sand from major sand source areas at home and abroad have been systematically evaluated to master the quality of sand in China and provide basic data for field fracturing design. In accordance with the API standard, the comparative analysis has been carried out between Ottawa sand (Northern white sand) and Brady sand (brown sand in Texas) that are commonly used in the U.S. and the sand samples from Inner Mongolia, Chengde, Xinjiang and many other regions. The analysis results indicate that the sand in China is a polycrystalline/monocrystal mixture, with the sphericity not smaller than 0.6; the crushing resistance level of 40/70-mesh and 70/140-mesh sand in China can reach as high as 4K-5K (about 28MPa-35MPa), which is equivalent to American brown sand, and the crushing rate value of the sand is basically approximate to that of the brown sand. Accordingly, the sand in China fully meets unconventional reconstruction demands, and the application and promotion of sand in China (as shown in Figure 1) shall be strengthened. The particle size distribution of proppants does not affect only their compression resistance but, more importantly, also the flow conductivity of proppant filling layers. The two most important factors affecting the flow conductivity of proppants are particle size distribution and crushing resistance.

![Figure 1. Crushing resistance of 40/70 mesh and 70/140 mesh sand at 35MPa.](image)

3. Basic theoretical research

In order to study the feasibility of sand application technologies, the proppant types, sizes, sand-carrying fluids and pumping procedures appropriate for different reservoirs are preferred; the basic research on the economic flow conductivity of proppants is strengthened; scientific, economic and optimal design methods for sand are established; then, the overall level of research and the fracturing design and technology is improved. Additionally, the load-carrying and migration mechanism of proppants in unconventional reservoir reconstruction is disclosed, and the method for improving the flow conductivity of fractures is proposed.

3.1. Effective closure stress analysis for proppant

The derivation of proppant force formula and numerical simulation reveals the stress state of proppant under unconventional horizontal well multi-stage reconstruction mode. The closing pressure, acting on the proppant, is the difference between the bottom-hole operating pressure (theoretically, the minimum
principal stress) and the reservoir pore pressure. During production, the pore pressure gradually decreases, and the closure stress increases accordingly. The rate of change of the closing pressure is closely related to the permeability and drainage rate of the original matrix. Since the permeability of unconventional reservoir matrix such as tight oil and gas reservoir and shale gas reservoir is lower than that of conventional oil and gas, and the unconventional oil and gas wells are basically horizontal wells, during the hydraulic fracturing construction, small cluster spacing, large-displacement large-scale liquid injection, and low-viscosity slick water or low-concentration guar gum, small-particle-size proppant, well killing and other measures are adopted to extend the impact scope of the liquid, greatly increase the pressure in the matrix pore and hydraulic fracture, lower the drainage rate, reduce the increase rate of closing pressure, and alleviate the stress of the proppant. Taking Mahu as an example, more than 600 days of production performance analysis indicates that under the large-scale multi-stage multi-cluster injection mode of horizontal well, the effective stress of proppant is only 50–60% of that in vertical wells (45–50 MPa). The stress state of proppant in horizontal well is reconsidered, breaking the conventional principle of selecting proppant according to the closure stress of the reservoir.

3.2. Methods for improving fracture conductivity

Figure 2 shows the curve of conductivity varying with the closure stresses of 70/140-mesh sand at the laying concentration of 10 kg/m², 5 kg/m², 2.5 kg/m² and 1.25 kg/m². The results indicate that the higher the laying concentration, the greater the conductivity; the increase in the conductivity is almost the same as that in the concentration; the permeability is an inherent property of the proppant, and the permeability will not change with the laying concentration; the permeability is only related to closure stress. Due to the action of the sealing rubber ring of the conductivity chamber and the restriction of the laying uniformity, the measured conductivity at the low laying concentration is relatively high.

In the production response of horizontal shale oil and gas wells, the proppant can be used to make up for the losses due to the natural sand with poor quality. A typical horizontal well has hundreds of hydraulic fractures, which leads to more oil gas flow into the wellbore, which means that the proportion of each fracture to total oil and gas flow can be reduced. Consequently, the demand for fracture conductivity will be significantly reduced.

The physical model test shows that the sand has a low density, with the farther migration distance and the higher laying uniformity, so that the silt is more likely to enter the hydraulic fracture branch (Figure 3).

Figure 2. Conductivity of 70/140 mesh sand at different laying concentrations.

Figure 3. Sand-containing rheological visualization proppant evaluation test.
4. Localization of sand source

The most ideal proppant is solid, crush-resistant, corrosion-resistant, low-density, and inexpensive. Therefore, choosing an economical proppant is a difficult task. The proppant shall be capable of withstanding stress, time/corrosion, fluid and crushing, and highest possible conductivity. For a long time, sand from local sources has been regarded as a low-quality proppant material, as compared with conventional high-quality fracturing sand, the local sand usually has lower compressive strength, sphericity and roundness, containing higher mineral "impurities". However, in recent years, as the sand from local sources are close to the hydraulic fracturing site, thus reducing the transportation cost, technicians and service companies have reconsidered it.

The current production capacity of sand is about 3.2 million ton/year in China. It is estimated that, during 2021~2025, PetroChina's annual demand for sand alone is about 4~6 million ton/year. Therefore, selecting an economic proppant is an arduous task. The sand under development is mainly distributed in Qingshankou of Ningxia, Weichang of Hebei province, Chifeng and Tongliao of Inner Mongolia, they are the northern aeolian sand. PetroChina's unconventional oil and gas resources are mainly concentrated in Sichuan province (south of China), Xinjiang Region (northwest of China), Changqing Oilfield and Daqing Oilfield. The production cost of sand is about 260 RMB/ton, and the cost of transporting sand from the north to Sichuan province, Xinjiang Uygur Autonomous Region and other places is about 450~700 RMB/ton. Therefore, the localization of sand source is an effective means to reduce the costs of proppant. Regarding the Sichuan Basin and Junggar Basin, key areas for unconventional oil and gas development, relevant units are organized by PetroChina to carry out the localized sampling, analysis, and evaluation of sand in Xinjiang Uygur Autonomous Region, Sichuan province, and the Yangtze River Basin, as shown in Table 1 & 2. The evaluation results show that: The quality of westerly aeolian sand from Xinjiang Uygur Autonomous Region is equivalent to that of American yellow sand. At present, a modern sand plant, with an annual production capacity of 500,000 tons, has been built, meeting the needs for capacity construction of Mahu and Jimsar, and the internal localized construction of the sand plant has been initially promoted, thus guaranteeing the long-term self-supply of proppant. Rock ore sand from Jiangyou of Sichuan province and Chuxiong of Yunnan province have the same sand crushing resistance and conductivity as the northern aeolian sand, of which the content of ore sand from Jiangyou is more than 98.6%, the single crystal structure is mainly 70/140-mesh silt, and the roundness and sphericity of Jiangyou sand is slightly poorer than that of Inner Mongolia sand used on site, but it meets the relevant standard. The performance of 70/140-mesh sand from Jiangyou meets the requirements of shale gas fracturing proppant, and its crushing rate and conductivity are slightly better than that of Inner Mongolia sand adopted on site.

### Table 1. 40/70 mesh sand from local sand source.

| Origin          | Chengdu | Jiangyou | Yiliang | Guangyuan | Zhaozhuang | Xuyong | Jimusar | Dixi | Zhundong | Shixi |
|-----------------|---------|----------|---------|-----------|------------|--------|---------|------|----------|------|
| Bulk density (g/cm³) | 1.35    | 1.36     | 1.3     | 1.26      | 1.33       | 1.34   | 1.48    | 1.46 | 1.53     | 1.47 |
| Roundness       | 0.7     | 0.62     | /       | 0.6       | 0.63       | 0.7    | 0.71    | 0.73 | 0.72     |      |
| Sphericity      | 0.7     | 0.64     | /       | 0.6       | 0.73       | 0.7    | 0.78    | 0.77 | 0.78     |      |
| Crushing rate (%) | 45.1    | 14.5     | 30.7    | 34.9      | 17.2       | 22     | 18.4    | 24.4 | 33.2     | 11.4 |

However, the sand source from Jiangyou is ore stone, featuring relatively complicated production process, requiring four additional production steps of "blasting-quarrying-crushing-grinding", and increasing the comprehensive mining cost. Considering that, it is necessary to further explore superior ore sources. In addition, the sand from Yiliang of Sichuan province has the potential for further excavation. The crushing rate value of channel sand in the Yangtze River Basin under the closure...
stress of 35MPa is higher than 30%, which fails to meet the construction requirements of field hydraulic fracturing.

Through the comparison of the full cost calculation, the sand used in the basin will lower the total price by 230~260 RMB/ton compared with the northern desert sand, with a decrease of about 20%~30%, so that the cost of a single well is reduced by about 300,000 RMB based on the replacement of ceramic with sand.

The hard ore is crushed and used to produce the sand proppant, but the crushing operation of the ore and the rounding treatment greatly increase the production cost. Moreover, during crushing, the crystal structure is also damaged, affecting the strength of sand proppant and making it impossible to use it in the hydraulic fracturing construction.

The next step will be to accelerate the construction of sand plant near the oil and gas field and support localized proppant industrial bases with multiple sand sources. At present, the transportation cost accounts for 40~60% of the cost of sand, and the construction of the sand plant near the oil field can not only significantly lower costs, but also reduce dependency on external market and stabilize prices. Therefore, it is recommended to strengthen the support efforts for the three sand plants built in Xinjiang Uygur Autonomous Region and Changqing Oilfield, and to expand production scale. Meanwhile, potential high-quality sand mines in Songliao Basin, Sichuan Basin and other areas shall be surveyed and demonstrated to gradually improve the sand self-support and self-supply capacity of oil and gas field enterprises, and effectively control the cost and quality source of fracturing proppant.

Table 2. 70/140 mesh sand from local sand source.

| Origin    | Chengdu | Guangyuan | Zhaotong | Jiangyou | Xuyong | Chuxiong | Yiliang |
|-----------|---------|-----------|----------|----------|--------|----------|---------|
| Bulk density (g/cm³) | 1.22    | 1.33      | 1.3      | 1.36     | 1.25   | 1.31     | 1.28    |
| Roundness | 0.6     | 0.6       | 0.61     | 0.69     | 0.66   | 0.64     | 0.65    |
| Sphericity| 0.7     | 0.7       | 0.78     | 0.66     | 0.62   | 0.66     | 0.68    |
| Crushing rate (%) | 35MPa (5K) | 25        | 18.8     | 19.2     | 7.5    | 20       | 8.2     | 13.7 |

5. Field application

On the basis of the feasibility evaluation study, the top-level design is strengthened, the comparative pilot test of replacing ceramic with sand for shale gas and tight oil is conducted in an orderly manner, and six demonstration zones for the promotion and application of sand in Ordos, Mahu, etc. are established. The amount of sand increased from 650,000 tons in 2015 to 2.75 million tons in 2019, the proportion increased from less than 46%~69%, and the cost savings were about 1.5 billion RMB in two years.

Through tracking and analyzing the initial and long-term (more than 2 years) production dynamics of more than 50 sand test wells and ceramic control wells in Mahu Oilfield of Xinjiang Uygur Autonomous Region, it indicates that the reduced costs for a single well is 1.35~3.48 million RMB, and the cost reduction per one million tons of production capacity is more than 300 million RMB. This fully proves that sand is an effective and feasible alternative to ceramic, showing a broad prospect for economic benefits. In 2018, the fracturing scale comparison test had been continued for Jimusar horizontal well, to determine a reasonable scale of reconstruction. Well J1/2 has a sanding intensity of 3.0 m³/m and a fluid intensity of 46.9 m³/m, of which Well J2 has a sanding capacity of 4,550 m³ and fluid capacity of 70,069 m³, reaching a new high volume fracturing scale for horizontal wells in Xinjiang Oilfield. The well has been put into production for 21 days, with the production results better than Well J3/4.
In 2018, the refracturing application was carried out for nearly a thousand of horizontal wells and old wells in Changqing Oilfield. The results indicate that the sand basically meets the requirements for the conductivity of micro-fracture, branch fracture, and main fracture in Changqing tight oil formations. The application results of typical wells on two platforms of southwest shale gas indicate that there is no obvious change in the single-stage gas output when the proportion of sand is increased from about 30% to 70%~80%.

6. Conclusion
(1) Compared to the American brown sand, the sand used in China has equivalent crushing resistance and conductivity. Therefore, sand in China fully meets the requirements of unconventional reconstruction;

(2) Based on the differences characteristics of the reservoir and fluid and completion methods between unconventional and conventional oil and gas, it is confirmed that the beneficial development of unconventional oil and gas can be realized by increasing the laying concentration and using small-particle-size sand;

(3) The feasibility of localization of sand sources is carried out, demonstrating that Shixi, Jiangyou, Yiliang and Chuxiong have certain development potential, thus laying a resource foundation for further cost reduction and benefit increase of unconventional oil and gas;

(4) The field test indicates that the current sand for fracturing in China fully meets the technical requirements of the unconventional reservoir reconstruction with a depth of 3,500 m or less, showing good production results and economic efficiency.

Based on the above research and understanding, the cost reduction and benefit increase of sand shall be further improved to ensure the low-cost development of oil and gas in China, and the promotion and application of sand and the construction of a nearby sand plant shall be strengthened.

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