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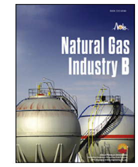
Natural Gas Industry B xx (2016) 1—11



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Research Article

Technical ideas of recovery enhancement in the Sulige Gasfield during the 13th Five-Year Plan☆

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Received 13 November 2015; accepted 9 May 2016

Abstract

Based on the exploration and development achievements of the Sulige Gasfield in the Ordos Basin, tight sandstone gas yield has been increased essentially in China. Recovery enhancement is always the core subject in researches. In this paper, the development history of the Sulige Gasfield was reviewed focusing on the technological progress in single well production enhancement. Then, the technical ideas on and countermeasures for transforming the traditional development modes and increasing recovery factor were discussed. It is shown that the development technologies in the evaluation and the production enhancement and stabilization of giant tight sandstone gas reservoirs are changed progressively. The fast increase of gas production in this field is made possible by well location arrangement technology based on sweep spot screening, horizontal well development technology, well type and well pattern optimization technology, fast drilling technology, reservoir stimulation technology, drainage gas recovery technology and integrated construction mode. And finally, the technical ideas of recovery enhancement during the 13th Five-Year Plan were proposed in nine aspects, including gas field development, planning and evaluation technology based on single-well life cycle analysis; dynamic evaluation and infilling technology for mixed well patterns targeting recovery enhancement; one-shot recovery enhancement technology for a new areal pattern area with integrated multiple well patterns and multiple series of strata; reserve evaluation model based on risk and benefit evaluation; gas-well precise management technology with multi-dimensional matrix; potential tapping technology for low production and low efficiency wells; novel wellsite environmental protection technology; surface process based on integrated equipments; and C_3^+ mixed hydrocarbon recovery technology. It provides technically reliable support for the development of tight sandstone gas reservoirs in the Sulige Gasfield during the 13th Five-Year Plan.

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Keywords: Ordos Basin; Sulige Gasfield; Tight sandstone gas reservoir; Heterogeneity; Development technologies; Recovery factor; Comprehensive research; Scheme

Tight sand gas is an unconventional gas developed on the largest scale in the world. It is characterized by widely contiguous distribution, absence of gas—water contact (GWC) and unapparent gas reservoir boundary [1—8]. Tight sand gas in China is characterized by thin gas layer, low gas saturation, low reserve abundance and large burial depth [9—16], making it more difficult to be economically developed than abroad. Now, China is entering a new period when equal attention is

☆ Project supported by the National Major Scientific and Technological Project, "Demonstration Project of Large Low-permeability Lithologic-stratigraphic Oil and Gas Reservoirs in Ordos Basin" (Grant No. 2011ZX05044) and the CNPC Scientific Research and Technical Development Project, "Major Engineering Technologies for Development of Tight Gas Reservoirs" (Grant No. 2012E-1306).

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Peer review under responsibility of Sichuan Petroleum Administration.

http://dx.doi.org/10.1016/j.ngib.2016.05.008

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paid to conventional and unconventional gas development [17–23]. The innovation of development techniques [14–16,24–42], and especially the breakthrough in geologic theories [43–47], allows for the economical and effective development of some low-quality tight sandstone gas reservoirs that could be developed only with low or even no benefits [36,48,49]. Tight sand gas, with its proved reserves in place accounting for more than 40% of the total proved gas reserves in China, has become the main force for increasing gas reserves and output in China. The Sulige Gasfield in the Ordos Basin and the Upper Triassic Xujiahe gas reservoir in central Sichuan Basin are the typical representatives of tight sand gas [9–16,22–49]. It has become a consensus to preferentially develop tight sand gas among unconventional gases [8–22].

The Sulige Gasfield is an onshore tight sand gas field with the largest proved reserve in China. Its output reached 235.3×10^8 m^3 in 2014, accounting for more than 65% of the total tight sand gas output of China in that year [22,23]. Thereby, it has promoted the development of tight sand gas in China to achieve a qualitative leap, and has made a great contribution to the alleviation of tight gas supply and demand situation in China. By virtue of solid geoscience theory, scientific storage and production technology, advanced and applicable principles and rational resource allocations, the tight sand gas reservoir development project of the Sulige Gasfield was awarded one of the three excellently executed projects in the 6th International Petroleum Technology Conference and Exhibition (IPTC) held in 2013. It was the first international award and recognition obtained by China in the field of tight sand gas reservoir development. The gas field is characterized by low permeability, low pressure, low yield and strong heterogeneity [22–28,36,48]. The major geologic conditions for the formation of large tight sand gas reservoirs in the gas field include gentle structures, wide distribution of source rocks, stable sedimentation, wide distribution of reservoirs, constructive diagenesis, distribution of relatively high permeability reservoirs, and short range migration and efficient accumulation of gas, etc [15,36]. The reservoir is highly heterogenetic and its physical properties are poor, resulting in low single well controlled reserve. When a vertical well is used for development, the single-well output is low, the production decline is fast, the production plateau is short and the recovery percent of reserves is low [23–28]. Furthermore, the ecological environment of the work area is fragile. Therefore, it is faced with many technological challenges to achieve the targets of improving gas recovery, reducing development cost and building a green and harmonious gas field [22–25]. In view of this, by reviewing the development history of the Sulige Gasfield and systematically summing up the key technologies for scale and beneficial development, this paper analyzes the progress of technologies for enhancing single-well output and discusses the technical countermeasures for transforming the traditional development mode and improving gas recovery, in the hope of presenting valuable information and tamping technical base for a long-term stable production of the gas field and a smooth supply of gas in China.

1. Development history and main achievements

The Sulige Gasfield, located in the northwestern Yishan slope of the Ordos Basin, is a gentle west-dipping monocline. The main gas-bearing zones consist of fluvial sandstone reservoirs of the 8th member of Lower Shihezi Fm and the 1st member of Shanxi Fm of Permian, Palaeozoic, characterized by low permeability, low pressure, low yield and strong heterogeneity, with a burial depth of 3000–3600 m and a thickness of 140–170 m. The sedimentary environment is a terrestrial braided river sedimentary system on the whole, and can be divided into channel bar, channel fill and flood plain microfacies. Widespread lithological traps are developed, and the sedimentary environment can be divided into 4 zones (east, central, west and south) [23–25]. The exploration area is 5.5×10^4 km^2, with the total gas resources exceeding 5.0×10^{12} m^3, the submitted proved and basically proved gas in place being 4.0×10^{12} m^3, and the cumulative gas output being more than 1240×10^8 m^3. It is a gas field with the largest reserve scale and the highest annual and cumulative gas output in China up to now.

Large-scale natural gas exploration started in 2000 in the Sulige area, when 120×10^4 m^3/d high-yield absolute open industrial gas flow was obtained from the 8th member of Lower Shihezi Fm in Well Su 6, and 5336.52×10^8 m^3 uncompartmentalized proved gas in place (GIP) was submitted, marking the discovery of the Sulige Gasfield. Afterwards, in the light of the exploration concept on large lithologic gas reservoirs (namely, exploring facies belts in the whole area, anatomizing main sands on the whole, and evaluating high permeability areas intensively), a total of 40 exploration wells were deployed, but the test outputs were largely different. Therefore, as a new type of resources in China, tight sand gas reservoirs are face with challenges in terms of reservoir recognition and development strategies. By virtue of strengths throughout PetroChina, major technologies are formed for different development stages, contributing to the finalization of the largest gas field in China and a great-leap-forward development of similar gas reservoirs. The development history of the Sulige Gasfield can be divided into three stages, i.e. evaluation, production enhancement and production stabilization. Currently, the Sulige Gasfield is at the production stabilization stage. The main development technologies exhibit a "progressive change" – from qualitative to quantitative evaluation, from overall framework to classification evaluation, from single well to well cluster production, and from single well pattern to multi-well mixed areal well pattern production. Supporting technologies are changing from import techniques to independently-developed techniques, factory-like operation and volume fracturing. Surface technologies are developed towards skid-mounted modes and digital modes. With these changes, single-well output and recovery factor are expected

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to increase and the development cost is expected to decline stably.

1.1. Evaluation stage (2001−2005)

During 2001−2005, substantial preliminary evaluations related to fracturing and production test were conducted. As a result, it is recognized that the Sulige Gasfield is a widely distributed low-permeability, low-pressure and low-abundance gas field, which cannot be effectively developed by conventional techniques. Multiple-method analysis (incl. dynamic analysis) shows that the effective sand scale is only 0.22 km^2. Hence, the development approach of "relying on science and technology, innovating mechanism, simplifying exploitation, and developing at low cost" was established, and the development target was adjusted from pursuing single-well "high yield" to pursuing "overall effectiveness". Moreover, stable single-well production was defined at 1×10^4 m^3/d for 3 years. Thus, the development of the Sulige Gasfield was guided into a new stage. In addition, a series of development techniques were ascertained, which are represented by post-stack inversion, underbalanced drilling, air drilling, large-scale commingled fracturing and bleed production; the concept of classification gas well evaluation was established, and the production indexes of vertical wells were clearly determined.

1.2. Production enhancement stage (2006−2013)

This stage can be divided into two sub-stages: (1) economical and effective development sub-stage (2006−2008), when the objectives were to ensure that the proportion of Type I and Type II wells reaches 80% and that the single-well investment steadily drops to the critical point of benefit; and (2) development level and benefit promotion sub-stage (2009−2013), when the objectives were to improve the single-well output and gas recovery. By means of innovating the cooperative development mode and the construction mode, 12 supporting development technologies represented by well location optimization technology, fast drilling technology, reservoir stimulation technology, downhole throttling technology, interwell cascade connection technology and digital management technology were formed in the Changqing Oilfield, and the basic well pattern and major technologies for the development of the Sulige Gasfield were established [14,15,23−33]. The development well type changed from vertical wells and cluster wells into horizontal wells [23−30]. Reservoir stimulation evolved from multiple intervals in vertical wells to multiple sections in horizontal wells, multiple fractures within a section and volume fracturing, with up to 13 fractured intervals in a vertical well and more than 20 fractured sections in a horizontal well [29−31]. The production management evolved from man patrol to digital and intelligent management, the tubing and casing were localized, and the surface flow was further simplified and optimized [32,33]. As a result, the development level was significantly improved, and the targets were accomplished two years ahead of the schedule.

1.3. Production stabilization stage (2014−today)

There is a lack of effective means for macro-analysis on the long-term stable production of the Sulige Gasfield. The difficulties in stable production are mainly manifested in seven aspects: (1) effective reservoirs largely change in 3D space; (2) imperfect well pattern results in low reserve-producing level; (3) different reservoir and fluid characteristics result in uneven production decline; (4) complicated gas−water relation makes it hard for some reserves to be effectively produced for the moment; (5) the number of gas stringers increases with the continuation of production; (6) the effects of different exploitation modes are different; and (7) the enhanced oil recovery techniques are not suitable [23]. Following the idea of "spatial avoidance, time staggering, reliance on technology, and enhancing production by stimulation", priority of development is given to the selected enrichment areas, the secondary reserve areas are avoided temporarily, and the development of the blocks with low economic benefit are postponed. Then, with the transformation of the traditional development mode and the pursuit of the enhanced gas recovery as the core [14,15,23−27], and the improvement of single-well cumulative gas recovery as the objective [23], efforts are reinforced in technology research to realize the target of long-term stable production of the gas field.

2. Progress of major development technologies

2.1. Well deployment technology based on sweet spot screening

The screening of "sweet spot" is one of the prerequisites for the scale and effective development of tight sand gas fields [14−16,50]. The effective reservoirs of the Sulige Gasfield greatly change in 3D space [23] and are highly subtle. Through R&D efforts, seismic reservoir prediction has realized conversions from analog to digital, from 2D seismic survey to 3D seismic survey, from post-stack inversion to pre-stack inversion, and from sand layer evaluation to gas layer prediction. Accordingly, the successive fine description can be carried out effectively "from channel belt identification to sand body prediction and gas layer prediction, and then to reservoir space depiction". Thus, the sweet spot screening technology for the Sulige Gasfield was established. Additionally, the well location optimization technology was optimized, and the development mode converted from vertical well to directional well and then to horizontal well [23−25]. As of today, the "sweet spots" selected account for 23.7% of the total gas-bearing area, and the proportion of Type I + II wells remains above 80.0%, contributing to the smooth implementation of the overall plan.

2.2. Horizontal well development technology

Horizontal well drilling is an effective means for increasing single-well output. The overall development technology of horizontal well includes clustered allocation, differential design, factory-like operation and skid-mounted station [23−25]. As to large tight sand gas reservoirs, the requirements for fine description of reservoirs are different depending on development stages. So it is necessary to further understand the reservoir configuration in different dimensions, and to describe the composite sands in intervals in terms of geologic setting, architecture type and sedimentary facies belt. On the basis of identification of sedimentary microfacies, sand superposition type and main channels, the composite sands in sublayers are depicted. Then, depositional periods/stages and single sands are divided and single sand scale is characterized to qualitatively define the single sand scale. Next, architectural elements are divided, architectural interfaces are identified, architectural element scale is quantitatively characterized, and spatial distribution of different elements is depicted. Finally, the remaining reserve distribution is ascertained. All these activities will provide a scientific basis for the deployment of clustered horizontal wells. Accordingly, three kinds of well deployment modes are worked out, and factory-like operation and skid-mounted station are adopted [23−26,29,30]. The number of wells drilled in a year increased from 10 wells in 2009 to 222 wells in 2013. The horizontal well productivity ratio increased from 5.1% at the initial evaluation stage to 60.8%. The penetration rate of effective reservoirs increased from 23.9% at the initial stage to 65%, and the initial output of horizontal well was 3−5 times that of the adjacent vertical wells.

2.3. Well type and well pattern optimization technology

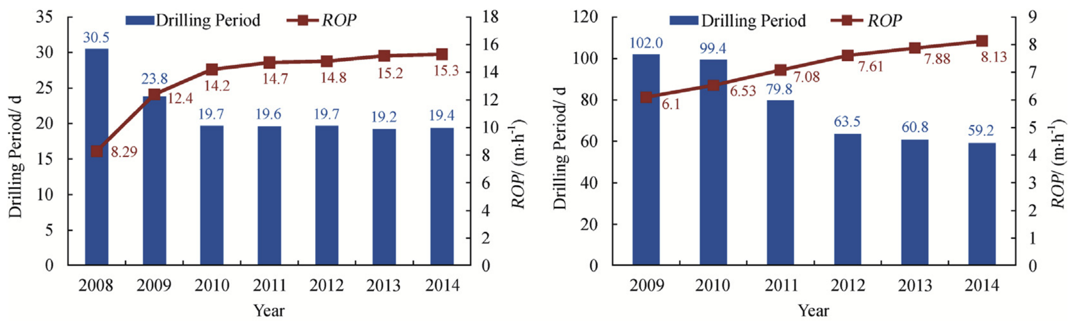
Research results and development practices show that well types and well patterns are principal factors influencing the recovery factor of tight sand gas fields with strong heterogeneity [23,27,28]. Under the current technical and economic conditions, higher development indexes are expected in addition to good economic benefit depending on the geological characteristics of gas fields. The reservoirs in the Sulige Gasfield have strong heterogeneity, such as a small scale of effective sandbodies and complicated superimposition. With the Su 6 infilling area as an example, an effective reservoir modeling method with hierarchical facies control and dynamic constraint was established on the basis of dynamic analysis results [23]. Guided by the multipoint geostatistics, with more dynamic constraint samples, an extended gas reservoir model was built. The concept of interwell interference was presented for the first time, and the relation between the interwell interference probability and the well spacing density was revealed. A variety of methods like fine anatomy of sandbodies, reservoir engineering, numerical simulation and economic evaluation were jointly used to build a mathematical model for the optimization of development well patterns, and a quantitative description of gas field recovery factor and well spacing density was derived. Then, on the basis of integrated analysis, a rational development well pattern was proposed for the Sulige Gasfield [27,28].

2.4. Fast drilling technology

In addition to the innovative integration of such technologies as PDC combined drilling, casing program optimization, accurate control of trajectory and low friction anti-sloughing drilling fluid system, the drilling design shifted from vertical well, clustered directional well and horizontal well to three-dimensional configuration with multiple well types and large well clusters [29,30,51]. Underbalanced drilling and slim-hole drilling field tests were conducted at the initial stage. By means of casing program optimization, PDC optimization design, drilling tool assembly optimization and casing localization, a cluster well drilling technology was vigorously developed. Through casing program optimization, wearable steering PDC design, and R&D of strong inhibition anti-sloughing drilling fluid system and low friction drilling fluid system, the horizontal well drilling was optimized. Based on 3D horizontal well drilling technology, anti-collision and obstacle-avoidance technology and factory-like mode, the fast drilling technology with multiple well types and large well clusters was studied and developed. By virtue of these measures and technologies, the average drilling period of vertical/cluster wells has dropped from 30.5 to 19.4 days, and the single-well drilling cost has dropped by 37.5%; the horizontal well drilling time has shortened from 102 to 59.2 days, and the single well drilling cost has dropped by 40% (Fig. 1). With the G07-6 well cluster as an example, the combination of 7 vertical/directional wells and 7 horizontal wells was adopted to develop the Upper Paleozoic and Lower Palaeozoic gas reservoirs in a three-dimensional way. In this way, an overall scale development was achieved, with shorter drilling period and lower cost.

2.5. Reservoir stimulation technology

In the case of vertical wells, in view of the characteristics of “multiple layers in one well, low yield from single layer” of the Sulige Gasfield, two sets of separate-layer fracturing technologies (i.e. mechanical packer and casing sliding sleeve) were developed in order to produce multiple layers simultaneously [29−31]. As for the mechanical packer separate-layer fracturing technology which adopts “large drift diameter packer, multihole ballseat, and multilayer stress profile design”, the number of fractured layers increases from 3 to 11, and the fracturing period drops from 2 to 3 days to only one day. Its application in 4000 wells demonstrates the success in fast separate-layer fracturing in multiple layers at a low cost, with the cost reduced by 25%. As for the casing sliding sleeve separate-layer fracturing technology which adopts “switchable casing sliding sleeve, soluble ball, constant pressure sliding sleeve, and reducing rubber plug”, the number of fractured layers can be up to 11. This technology has been tested in 192



a. Vertical/cluster wells b. Horizontal wells

Fig. 1. Drilling indexes of wells in the Sulige Gasfield.

layers of 48 wells, with tool price being 50% of the similar products abroad.

In the case of horizontal wells, depending on the characteristics of different reservoirs, two sets of horizontal well staged fracturing technologies (i.e. multistage sliding sleeve hydraulic sand blast and open hole packer) were developed [29]. They have been applied in 582 wells, with an initial flow rate being three times that of the output of vertical wells. A volume fracturing technology characterized by "fracture initiation by low viscosity liquid, sand carrying by high-viscosity liquid, multi-scale proppant combination, and high displacement large-scale injection" was established [52,53]. According to the monitoring results, the stimulated reservoir volume (SRV) was more than doubled, and the initial daily gas flow rate was 1.8 times that of conventional horizontal wells. Two sets of low-damage fracturing fluid systems (i.e. low-concentration and anionic surfactant) were independently developed for tight sand gas reservoirs, which allowed the core damage in laboratory assessment to drop below 20%. Furthermore, these two systems have been used in more than 2000 wells, with stimulation effect being 20–30% higher than conventional systems.

2.6. Water drainage and gas recovery technology

According to the production performance, after a fast production decline stage, gas wells in the Sulige Gasfield were observed to have apparent signs of liquid loading, such as violent fluctuation of output and pressure, over a period of production at low pressure. It suggested that the gas field would enter a water drainage and gas recovery stage. In such a case, certain drainage-supporting measures are required to prevent the liquid from affecting long-term stable production [23]. A series of water drainage and gas recovery technologies were formed, which are dominated by foam-aided water drainage and gas recovery, and aided by velocity string, plunger lift and gas lift reproduction. These technologies have contributed successive breakthroughs and have been improved and updated to challenge the fluid-carrying production cutoff of gas stringers [23]. The foam-aided water drainage and gas recovery has converted from artificial injection to remotely-controlled injection, with the effectiveness percentage exceeding 85%. The whole set of velocity string technology has been localized, with the treatment cost reduced by 50%. The plunger lift technology has been developed independently, and the wellhead artificial parameter adjustment has been converted into remote control parameter adjustment, reducing the treatment cost by 62.5%. In 2015 alone, yield increased by 17.0×10^{12} m^3 through water drainage and gas recovery in the Sulige Gasfield.

2.7. "Integrated" construction mode

A Sulige-specific surface construction mode of "downhole throttling, low-to-moderate pressure gas gathering, pre-knockout metering, interwell cascade connection, atmospheric temperature separation, two-stage supercharging and centralized processing" has been formed [32], which is suitable for the characteristics of the Sulige Gasfield such as numerous wells, low single-well output and fast pressure drop. For the purpose of effectively shortening the construction period and improving the management level, according to the principles of "miniaturization, skid-mounted pattern, integration, unitization, networking and intellectualization", a series of integrated facilities have been integrated and innovated, like gas gathering integrated facility, electric control integrated facility and condensate stabilization skid, and a new mode of "integrated" construction has been formed. Thus, a skid-mounted gas gathering station has been realized, the construction quality has been promoted, and the development benefit has been improved. The "integrated" construction mode has helped to realize the conversion from parts standardization to products standardization, expedited the surface construction, reduced the station floor area by more than 35% averagely, shortened the design period and the construction period by more than 30% and 35% respectively, and reduced the field installation workload by 80%. Therefore, this mode is the new direction in surface construction of the gas field [32,33].

3. Technical idea on improving gas recovery

Globally, 70% of the annually incremental reserves are contributed by the discovered large oil and gas fields [54], and the output of these gas fields is more vital to the oil and gas resources [20,21]. In a sense, it is more realistically

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significant to develop a discovered tight sand gas reservoir than to explore a (giant) large tight sand gas reservoir. Moreover, with basic theoretical researches deepened, especially the theory of "successive gas generation" of organic matters presented [43−45] and success in the natural gas industry of superimposed basins [48,49], the reserve increasing, production enhancement and stable production ranges and areas of tight sand gas reservoirs will be continuously expanded. In the Sulige Gasfield, the "sweet spot" is the preferred target for initial development of tight sand gas reservoirs. As the development advances, the physical test and production performance all show that the reservoirs beyond the physical property cutoff also may have certain gas supply capacity [23,50]. Furthermore, the ecological environment of the work area is fragile. Therefore, for the purpose of achieving the targets of improving gas recovery and economic benefit, reducing development cost and building a green and harmonious gas field as well as ceaselessly promoting the development effect, local "sweet spot" development needs to be converted into regional overall development, and then the traditional development mode is converted into a modern one.

3.1. Gas field development, planning and evaluation technology based on single well life-cycle analysis

Tight sand gas reservoirs have poor reservoir conditions, which result in large fluid filtration resistance, fast energy consumption and limited productivity of gas wells. Besides, because of the production demand, the gas well flow rate is not steady, but declines fast; with almost no production plateau, a gas well usually enters its decline stage as soon as it is brought to production [23]. Based on an analysis of the life-cycle production decline laws of gas wells, and combined with brought-in gas well proportion of the blocks over the years, block production decline characteristics are determined. Then, by means of block weighting, the production decline laws and annual decline productivity of the gas field are obtained, which have provided a basis for the productivity construction planning of the gas field at the production stabilization stage. The 28 gas wells that have been produced for more than 10 years in the Sulige Gasfield show that these gas wells have longer production time under low-pressure conditions [23]. The production contribution rate of vertical wells is obviously different from that of the same number of horizontal wells. Moreover, the production characteristics of the zones in the Sulige Gasfield are different. Therefore, there are certain errors when conducting simulation and prediction only relying on single wells. Consequently, the production decline laws of vertical and horizontal wells in their life cycles need to be calculated and predicted respectively, and the production decline laws should be ascertained by zones on the basis of anatomy of typical blocks. Finally, the production decline rate of the whole gas field can be figured out by means of numerical simulation, but the production performance data of the previous year should be supplemented year by year to conduct constraint and correction, to obtain the annual decline productivity, and provide scientific basis for the development planning of the gas field.

3.2. Dynamic evaluation and infilling method for mixed well patterns

Development well pattern, horizontal well development, gas well production mode, abandonment condition, water production from gas well, fine management of gas wells and so on are the factors affecting the gas recovery of tight sand gas reservoirs. The tight sand gas development practices abroad show that well pattern infilling is the major technology for improving the gas recovery of tight sand gas reservoirs [12]. Since the Sulige Gasfield development, for the purpose of deepening the evaluation and understanding on the gas reservoirs, four infill test blocks have been opened successively, including 105 vertical wells in total, and after infilling, the well spacing density becomes 2.8−5.1 wells/km^2. However, the infilled blocks have a small range and mostly concentrate on the central zone. With the Su 14 3D seismic survey area as an example, variable well spacing (500 m, 600 m) and variable array pitch (600 m, 700 m, 800 m) infilling tests were conducted in 2007−2009 (Table 1); 41 vertical wells (directional wells) were drilled, the gas-bearing area was 16.57 km^2 within the range of 5 well clusters, and the well spacing density was 2.5 wells/km^2. Interference test was conducted in 17 well clusters, and there was interference in 3 well clusters, indicating that the recovery factor of the well clusters was related to the well spacing density and the reserve abundance. In the place where the reserve abundance was low, if the well pattern was too dense, the single-well output could not reach the economic limit rate. The development well pattern optimization [27] based on dynamic features is a scientific and effective technique to determine the rational development well pattern for the moment, but the conformity of the model still needs improving by means of infilling well test, interference test and dynamic analysis to determine the rational basic well pattern. The reservoir property, superposed pattern of effective sands, interwell communication and reserve abundance are different among different zones of the Sulige Gasfield. Therefore, the understanding of the remaining reserve distribution in different areas needs deepening further relying on dynamic data, and the production scale optimization and development effect evaluation should be conducted by means of studying the optimization of mixed well patterns in undeveloped areas and the well pattern infilling replacement mode of the developed areas as well as on the basis of reserves classification evaluation and producing condition analysis of reservoirs with different physical properties.

3.3. One-shot gas recovery improving technology for a new areal pattern block with integrated multiple well types and multiple series of strata

In the course of development, physical test and production performance all show that the reservoirs beyond the physical property cutoff also have certain gas supply capacity [23,50].

Table 1
Production index prediction on different well patterns in the Su 14 3D seismic survey area.

Well pattern/m	Test area/km^2	Reserve abundance/(10^8 m^3 km^{-2})	Dynamic reserves/10^8 m^3	Cumulative gas production up to now/10^8 m^3	Predicted average cumulative gas production of wells/10^4 m^3	Predicted cumulative gas production of block/10^8 m^3
500 × 600	4.18	1.25	1.86	0.80	1345.2	1.48
500 × 700	2.99	1.56	1.79	0.68	1957.2	1.57
500 × 800	2.98	1.80	2.40	0.80	2577.9	1.80
600 × 600	3.22	2.62	3.80	1.46	4013.4	3.21
600 × 700	3.21	1.36	1.71	0.79	1893.5	1.33

Furthermore, the ecological environment of the work area is fragile. As a result, it is a development trend to convert "sweet spot" development into overall development. The "factory-like" fracturing operation method and the surface process optimization technology for forming a complete well pattern system of the Sulige Gasfield [29—33] have provided a strong support for the one-shot development deployment of a new areal pattern block with integrated multiple well types and multiple series of strata. Multiple successive closure verification of framework profile should be adopted to build a stratigraphic framework of the study area that takes single sand as its target. The "hierarchy analysis, pattern matching and multidimensional interaction" architecture analysis should be conducted and a geologic model should be built by using the dense well pattern dissection results of adjacent developed blocks and seismic data and by comparing the proportion and production performance of Type I, II and III wells to describe the scale and distribution of effective single sands. Clustered multiple well types and multiple horizon development well deployment should be conducted to deploy the basic well pattern all at once. In addition, drilling results should be used to modify the geologic model in real time and conduct mixed well pattern optimization. Based on the drilling operation mode of well clusters, by means of optimized drilling sequence, batch drilling and multi-rig teamwork [51], the drilling efficiency can be improved, and the well cluster construction time can be shortened. As for the block that has not been put into development, such type of development can be used to achieve the target of changing the traditional development mode, thus improving gas recovery and economic benefit and reducing development cost.

3.4. Risk and benefit based reserve evaluation model

Globally, 70% of the annually incremental reserves are contributed by the discovered large oil and gas fields [54]. Therefore, successful classification evaluation on the proved reserves and ascertaining the key indicators of tight sand gas reservoirs at each development stage are an important basis for working out a scientific and rational development plan and determining the development investment scale. In combination of dynamic data with static data, and based on economic benefit, the reserves are evaluated and classified into enrichment zone, tight zone and water-rich zone (Table 2). Produced and remaining producible reserves evaluations are conducted. As for the area with relatively low well control level, the producing reserves of single wells are accumulated. As for the area with 80% well control level, the producing reserves are figured out using the product of delineated area and average reserve abundance. Then, the remaining reserves of different zones are obtained by accumulation. In different types of reserve areas, the reserve quality varies greatly, and the single-well output and production decline laws are also different. On the basis of the old wells that have been produced for a long time, and considering the interwell interaction after infilling, the prediction is conducted by classification. By combining the gas well productivity indicators and reserve scales, in light of reserve quality (from good to poor), the reserve producing analysis is conducted. Depending on different basic well patterns, in light of the producing sequence from the enrichment zone, tight zone to water-rich zone, the reserve producing model is built. Gas price is one of the most sensitive factors influencing the rate of return [23,25]. The evaluation results of remaining producible reserves are different at different gas prices. As the gas price rises, the remaining producible reserve increases gradually, the stable production period is prolonged, and the well pattern becomes small. Therefore, a model for producible reserve fluctuation at different gas prices should be built.

3.5. Multi-dimensional matrix gas well management technology

Diversified classification management of gas wells is the key to the effective development of gas fields [23]. It is an effective technology to increase the cumulative gas recovery of single wells to fully establish a hierarchical and systematic management system and form differential management technical countermeasures of gas wells (Fig. 2). However, the working system of intermittent flow wells and water producers needs further optimizing. Systematic research should be conducted on the foam drainage and filling-up timing of gas wells in terms of critical fluid-carrying rate, kinetic energy factor and liquid-holding rate, and on the optimization of intermittent flow well working system. In view of the percolation characteristics of low-permeability gas wells, the "long shut-in and short gas flow" system can allow for less difficulty in gas well management and is more favorable for exerting the gas-well deliverability than the "short shut-in and short gas flow" system. Moreover, with the former system, the current production is not affected. Therefore, field practice and evaluation efforts should be increased.

Table 2
Classification evaluation criteria for reserves in the Sulige Gasfield.

Reserves classification	Proportion of Type I + II wells	Reservoir parameter				Production performance			Economic index
		Net thickness/m	Porosity	Permeability/mD	Gas saturation	Single-well daily rate/10^4 m^3	Water—gas ratio/[$m^3 \cdot (10^4\ m^3)^{-1}$]	Cumulative production/10^4 m^3	
Enrichment zone	>75%	>6	>9%	>0.5	>55%	>1.0	<0.5	>1500	>12
Tight zone	<70%	3—8	6—9%	<0.5	45—60%	<1.0	<1.0	800—1500	8—12
Water-rich zone	<60%				45—55%	<0.6	>1.0	<800	<8

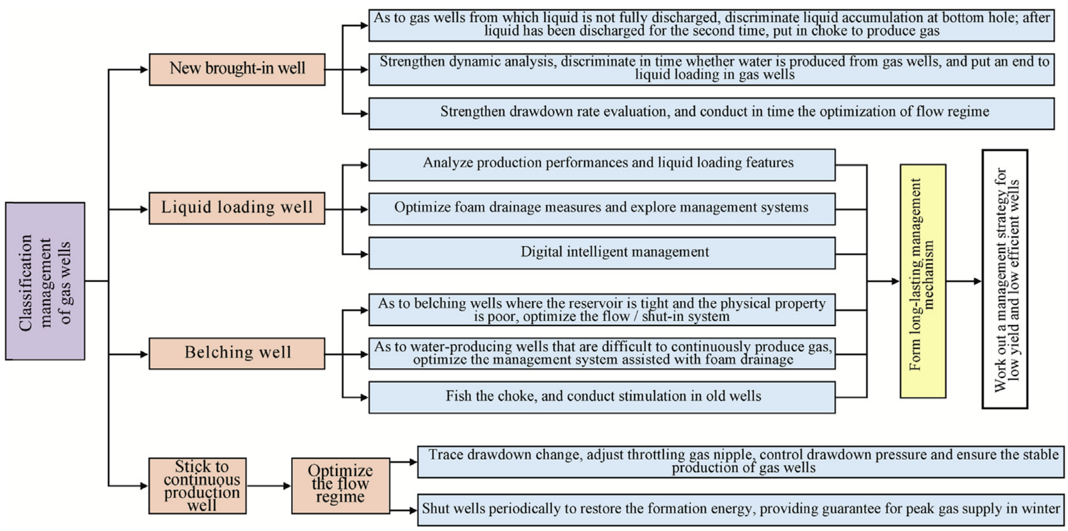

Fig. 2. Frame diagram of differential management technical countermeasures for gas wells.

3.6. Potential-tapping technology for low-yield and low-efficiency wells

The production period of gas wells in the Sulige Gasfield often exhibits three stages [23]. As the production time goes by, after a fast production decline stage, gas wells are produced at low pressure for a period. Then, apparent violent output and pressure fluctuation occur, and large number of gas wells gradually enters a production stage of low yield and water drainage and gas recovery. In order to further tap the potential of old wells for gas recovery enhancement, it is necessary to continuously work on the potential tapping techniques. Water drainage and gas recovery, old well sidetrack and old well repeated stimulation are the major technologies for tapping the potential of low-yield and low-efficiency wells. Major difficulties of water drainage and gas recovery are manifested in the research of water drainage and gas recovery technology of gas well life cycles and economical and effective water drainage and gas recovery technology for horizontal wells and big yield gas wells. Major difficulties of old well sidetrack are manifested in the limitation of slim-hole horizontal well length and high cost of imported sectional fracturing tools. Major difficulties of old well repeated stimulation are manifested in the voidage of reservoir energy, severe filtration of kill fluids, difficult propagation of old fractures, heavy fracturing fluid volume entering formations and difficult liquid discharge after fracturing. Through comparison, selection and demonstration of the applicability and the investment of gas well life cycle technology, velocity string technology is mostly adopted in Type I wells, whereas plunger lift technology is mostly adopted in Type II and III wells. However, key problems related to effective water drainage and gas recovery technology for horizontal wells and big yield gas wells still need tackling. Currently, the fracturing tools for sidetracked horizontal wells of the gas field are all imported from abroad, with their prices nearly three times that of the conventional Ø152.4 mm borehole tools in use. Therefore, research and development for localized tools are in an urgent need. Since drawdown cone area occurs in the reservoir after it has been produced for a long term, in the refracturing design, liquid N_2 or CO_2 is used as prepad to quickly form a high-pressure belt in the drawdown cone area around the borehole to reduce the fluid filtration in the course of fracturing and improve the fluid flowback velocity after fracturing. Liquid nitrogen injection pressurization and filtration-reducing refracturing pilot test were conducted in old layers of two wells, a daily production enhancement of 40—200% was obtained, but the fracturing technology and operation parameters still need to be assorted and optimized.

3.7. New wellsite environmental protection technology

For the purpose of protecting and improving environment, preventing pollution and other public hazards, ensuring public health, promoting ecological civilization construction and promoting the sustainable development of economy and society, Chinese government has issued a series of laws and regulations, which have put forward strict requirements for the environmental protection in the course of gas field development. Green processing of drilling and well test waste fluids, processing and resource utilization of solid wastes, and assorted environmental protection processing equipment are the new wellsite environmental protection technologies that are to be researched and developed urgently. "Reduction, reclamation and harmlessness" management and control are conducted on the wastes generated in the course of drilling and fracturing. Wellsite processing and centralized station processing are combined to allow the wellsite wastes to be processed without falling to the ground. In the course of construction, the drilling fluid and fracturing fluid are reutilized among the wells, and those used in the last well are transported to the centralized processing spot for processing. In the area where the productivity construction is relatively concentrated, skid-mounted or movable temporary waste water treatment spot is built to mainly process the drilling waste fluid and acidizing waste fluid, and also to process fracturing flowback fluid. After being processed, the fluid can meet the requirements of rejuvenated water and recirculated water indices; and the solid wastes are used to make bricks for paving wellsites and roads.

3.8. Integrated facility based surface process

As to such metering mode as "multiwell gas phase mixed metering of cluster well", mobile separate metering integrated facility is adopted on the cluster well site to periodically conduct metering on the gas and water of key monitoring wells, so as to meet the fine management requirement of gas wells. For the purpose of meeting small-scale desulfuration demand of remote smellers in the gas field, natural gas liquid sweetening integrated facility is in dire need of research and development, with a design scale of $5 \times 10^4 - 10 \times 10^4$ m^3/d, it covers small floor areas and is convenient for management and operation. To address the problem of instantaneous large water yield in some high water production blocks of the Sulige Gasfield, a new integrated facility with the function of produced water flashing, unloading and knockout is developed. It has the functions such as automatic liquid discharge, liquid level monitoring and alarming and remote control, and it can improve the reliability and stability of operation of large liquid volume stations. Gas−liquid multiphase flow is implemented in gas recovery main pipes in the horizontal well development area of the Sulige Gasfield. The main pipe diameter is large, slug flow easily occurs in the course of pigging, and the existing separator in the gas gathering station cannot meet the separation demand. As a result, a separation integrated facility suitable for slug flow characterized by instantaneous large liquid volume needs to be developed.

3.9. C_3^+ mixed hydrocarbon reutilization technology

The content of propane and heavier hydrocarbon components in the finished product gas of the Sulige Gasfield reaches 1%. According to the gas output of the Sulige Gasfield (235.3×10^8 m^3) in 2014, if the C_3^+ mixed hydrocarbon can be recovered, 32.8×10^4 t LPG and 10×10^4 t stable light hydrocarbon can be produced each year. Both LPG and stable light hydrocarbon are widely used. They can be used as industrial and domestic fuels, and also as industrial chemicals for deep processing to produce chemical products with high added value. They are prospective for marketing. The "pressure swing adsorption + low temperature separation" technology is adopted to primarily separate and purify the C_3^+ components; then, the resulted products enter the low temperature separation unit, and LPG and stable light hydrocarbon are obtained. This technology is characterized by low refrigeration load and high light hydrocarbon recovery. Although final gas product volume reduces, the economic benefit is promoted. The C_3^+ mixed hydrocarbon reutilization technology is one of the feasible methods to improve the development benefit of the gas field, but related field test needs to be conducted.

4. Conclusions

1) The development technologies in the evaluation, production enhancement and production stabilization stages of giant tight sand gas fields exhibit a "progressive change", namely, from qualitative evaluation to quantitative evaluation, from overall framework evaluation to classification and hierarchical evaluation, from single well production to multiwell cluster production, and from single well pattern production to multiwell mixed areal well pattern production. Supporting technologies convert from imported techniques to independently-developed techniques. Factory-like operation and volume fracturing become key technologies. Surface technologies are developed towards skid-mounted mode and digital mode. These technologies are utilized to finally increase the single-well output and recovery factor and steadily reduce the development cost.
2) The well deployment technology based on the screening of sweet spots, horizontal well development technology, well type and well pattern optimization technology, fast drilling technology, reservoir stimulation technology, water drainage and gas recovery technology and "integrated" construction mode support the rapid production enhancement of the Sulige Gasfield.
3) Nine development technologies will be urgently researched and developed, including gas field development, planning and evaluation technology based on single well life cycle analysis, dynamic evaluation and

infilling technology for mixed well patterns, one-shot improving gas recovery technology for a new areal pattern block with integrated multiple well types and multiple series of strata, risk and benefit evaluation based reserve evaluation model, “multi-dimensional matrix” fine management technology of gas wells, potential tapping technology for low-yield and low-efficiency wells, new wellsite environmental protection technology, integrated facility based surface process and C_3^+ mixed hydrocarbon reutilization technology.

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Please cite this article in press as: Tan ZG, et al., Technical ideas of recovery enhancement in the Sulige Gasfield during the 13th Five-Year Plan, Natural Gas Industry B (2016), http://dx.doi.org/10.1016/j.ngib.2016.05.008