Reserve Evaluation and Remaining Recoverable Reserves In Block X of the Sulige Gas Field

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Abstract: The Sulige Gas Field is a typical representative of China's tight sandstone gas fields. As the development of the gas field gradually deepens, evaluating gas field reserves and studying the distribution of remaining recoverable reserves are particularly important. Because of this, Sulige Gas Field Area X is used as a typical area for the research, which primarily focuses on the volumetric method to calculate geological reserves, supplemented by the geological modeling method to calculate the geological reserves, classify the reserve types, and apply geostatistical methods to analyze the degree of reserve control from the horizontal and vertical perspectives to determine the four distribution patterns of remaining recoverable reserves. The results show that: 1. A reserve classification and evaluation system with an internal rate of return as the core can divide geological reserves into four categories: I, II, III, and IV. The distribution is influenced by sedimentary facies and reservoir heterogeneity in the study area; 2. There are four types of remaining recoverable reserves: uncontrolled well network type, complex sand body edge type, isolated sand body with thin lost layer type, and incomplete perforation type; 3. Uncontrolled reserves are the mainstay of remaining recoverable reserves, accounting for 49.39% of the H8 layer and 58.58% of the Shan 1 layer; 4. The remaining unutilized reserves can be mobilized by measures such as drilling new wells between wells, planar reaming, and sidetracking old wells in order to mobilize the uncontrolled reserves, the imperfect perforation reserves, and the remaining reserves in the isolated sand body of the thin lost layer in the well network, ultimately achieving an overall increase in the degree of recovery of the gas reservoir.

Keywords: tight sandstone gas reservoir; Sulige gas field; reserve evaluation; remaining available reserves

1 Introduction

The Sulige Gas Field is a large lithologic gas reservoir with low permeability, pressure, and abundance[1-5]. A braided river sedimentary system formed the reservoir in an alluvial context. The effective reservoir is the coarse-textured zone in the braided river sandstone sedimentary system. The reservoir sand body is highly heterogeneous and

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has poor continuity, which results in low controlled reserves per well, low gas well production, rapid pressure decline, and poor stable production capacity, making gas field development very difficult[6]. At present, due to geological conditions and development technology constraints, the stable production prospects of the Sulige Gas Field face severe challenges. The reserves in the eastern and southern areas are low in abundance and difficult to develop profitably[7,8]. The gas-water relationship in the western area is complex and difficult to develop. The reserves in the central area are high in abundance, and the development results are good. However, it faces difficulties in well deployment and a year-on-year decline in production capacity. In order to extend the stable production life of the Sulige Central Area, this paper will take Area X as a typical area to carry out a study of the analysis of the reserves utilization in the study area, clarify the type and distribution law of the remaining reserves in the study area, and propose countermeasures to tap the potential of the corresponding types of remaining reserves.

2 Geologic Conditions of the Block

The study area is located in the northwest of the Yishan slope. From bottom to top, it is developed with the Benxi Formation, Taiyuan Formation, Shanxi Formation, Shihezi Formation, and Shiqianfeng Formation. Among them, the main gas-bearing formations are the Lower Shihezi Formation and Shanxi Formation, and the source rocks are the Shanxi Formation and Taiyuan Formation coal measures and dark mudstones. The study area is mainly developed with river-phase sediments, and the upper Shiqianfeng Formation mudstone is well-developed and has a good sealing capacity. In the tectonic evolution of the basin, no obvious fault development has been observed in the study area. The reservoir sandstone has undergone diagenesis, cementation, and replacement, which has destroyed a large number of primary pores but developed secondary pores, retaining a good storage space[6,9,10]. In summary, the study area has good source rocks, good storage space, preservation conditions, and the conditions for forming gas reservoirs. Exploration and development practices have proven that the distribution of the reservoir sandstone and its physical properties control the distribution of the gas reservoir.

3 Characteristics of Gas Reservoirs

The study area as a whole is a gently sloping monocline with a western dip, with a slope of 3–10 m/km. On the monocline background, there are multiple rows of low and gentle nose-like elevations that trend northeast–southwest, with a width of about 10–20 m. The overall distribution trend of the sand bodies in the Lower Shihezi Formation H8 is nearly north-south, with the sand bodies interweaving. Good reservoirs can develop in the foreland where the river meets. From the lower sub-section to the upper sub-section of H8, the range of sand distribution gradually decreases, and the lower sub-section of H8 is the main development layer of the sand body. The sandstone in the upper sub-section of H8 is distributed in a nearly north-south direction, and the sand body is relatively well developed. The reservoir rock type in the study area is mainly debris quartz sandstone, followed by quartz sandstone; the pore space is the main storage space, and fractures account for a small proportion.

The statistical analysis of the core analysis of the gas-phase sections of 89 cored wells in the study area shows that the porosity ranges from 3.0% to 20.2%, with an average of 8.75%. The main distribution range of porosity is 5% to 12%. The permeability ranges from 0.021 to $28.66\times10^{-3}\mu m^2$, with an average value of $0.756\times10^{-3}\mu m^2$. The main distribution range of permeability is in the interval of $0.065\text{-}1.02\times10^{-3}\mu m^2$, accounting for more than 80% of all samples. Overall, the gas layer is a low-porosity and low-permeability gas layer. The methane content of the gas components in the reservoir weathered gas in the study area is very high, averaging 92.5%; the average ethane content is 4.53%; the average CO_2 content is about 0.779%; it does not contain H_2S; the relative density is 0.6037; the average temperature gradient is 3.06°C/100m; and the temperature of the gas layer section is between 100 and 105°C.

H8 and S1 layer in study area belong to lithologic closed gas reservoirs. The sand body's distribution and physical properties control the reservoir's distribution. There is formation water, but there is no uniform gas-water interface. According to the gas reservoir pressure system analysis, the pressure coefficient is between 0.771 and 0.914, with an average of 0.87. Therefore, H8 and S1 layer in study area belong to low-porosity, low-permeability, low-pressure, constant-volume elastic-driven gas reservoirs.

4 Reserve Evaluation

4.1 Calculation of Reserves in the Study Area

A calculation method that uses the volumetric method of geological reserve calculation and is supplemented by geological modeling for verification is adopted to study the characteristics of the gas reservoir. According to the requirements of the "Calculation Methods for Oil and Gas" (DZ/T 0217-2005), the volumetric method is used to calculate the geological reserves in the study area, and the geology and temperature and pressure data in the study area are analyzed to determine the gas-bearing area, effective thickness, porosity, gas saturation, and original volume factor (see Tables 1 and 2).

Table 1. Reservoir pressure and temperature parameters in the study area

Parameter	H8	S1
Original formation pressure (MPa)	29.91	32.64
Ground standard temperature (K)	293	293
Standard pressure on the ground (MPa)	0.1	0.1
Mean stratum temperature (K)	381	384
Raw gas deviation coefficient	0.966	1.054

Table 2. Reservoir parameter table calculated using the volumetric method

layer	Porosity %	Saturation of Gas %	Effective Sand Thickness m	Gas-Containing Surface Area km^2
$H8_1$	6.51	58.24	4.93	230.00
$H8_2$	7.52	64.26	8.32	779.98
S1	6.84	60.41	7.32	648.17
Total/average	6.96	60.97	6.86	876.64

The study area of H8 and S1 has a combined gas-bearing area of 876.64 km^2 and calculated volume-based reserve of 1304.33×10^{8}m^3. The reserves are mainly distributed in $H8_2$ and S1, with smaller reserves in $H8_1$. The average abundance of the reserves is 1.49×10^{8}m^3/km^2.

Based on the geological knowledge base of the Sulige gas field, a hierarchical multi-point geostatistical 3D model of the fluvial facies reservoir was established. With the support of hard data such as logging data and core data, a structural model, a sedimentary facies model, an attribute model, a net-to-gross ratio model, etc., were established, respectively. The combined gas-bearing area of the H8 and S1 formations is 842.92km^2, and the calculated geological reserve is 1299.32 × 10^{8}m^3.

Comparing the calculated geological reserves using the volume method with those calculated using the geological modeling method, the error in the calculated reserves is less than 3%, indicating that using the volume method to calculate the geological reserves in the study area is accurate (Table 3).

Table 3. Calculation of geological reserves

Layer	Surface Area Containing Gas km^2		Geological Reserves 10^{8}m^3		Abundance of Reserves 10^{8}m^3/km^2	
	Volume Method	Geological Modeling Method	Volume Method	Geological Modeling Method	Volume Method	Geological Modeling Method
$H8_1$	230.00	217.70	101.78	98.70	0.44	0.45
$H8_2$	741.65	749.20	741.65	745.30	0.95	0.99
H8	/	784.61	843.43	844.00	/	1.08
S1	685.56	623.70	460.90	455.32	0.71	0.73

4.2 Evaluation of Reserves in the Study Area

A reserve classification and evaluation system with an internal rate of return as the core is constructed by comprehensively considering multiple parameters, such as the distribution of sedimentary facies in the study area, the sand body superposition model, and the production characteristics of gas wells[11,12]. According to the current gas price of 1,119 CNY/1,000 cubic meters, the EUR value of gas wells corresponding to different internal rates of return is calculated by comprehensively considering economic evaluation parameters such as gas well abandonment costs, urban maintenance and construction taxes, educational surcharges, and resource taxes. Among these, the comprehensive investment of a single well is 7.8 million yuan, the investment loan ratio is 45%, the bank loan interest rate is 4.9%, the unit operating cost is 0.12 CNY/m^3, and the production method is used for depreciation. The calculation shows that the EUR corresponding to an internal rate of return of 0 % is 1170×$10^4 m^3$, the EUR corresponding to an internal rate of return of 6% is 1320×$10^4 m^3$, and the EUR corresponding to an internal rate of return of 8% is 1490×$10^4 m^3$ (Figure 1).

Integrating various parameters, both static and dynamic, enhances benefits. Reserves are classified into four types: I, II, III, and IV (Table 4).

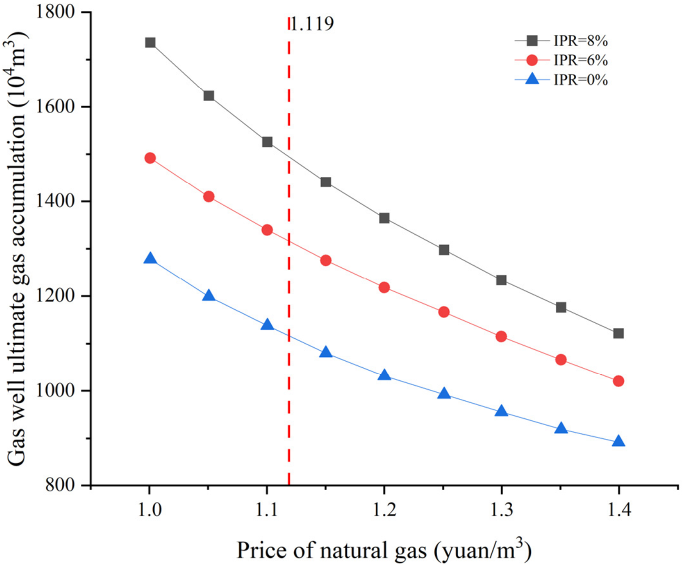


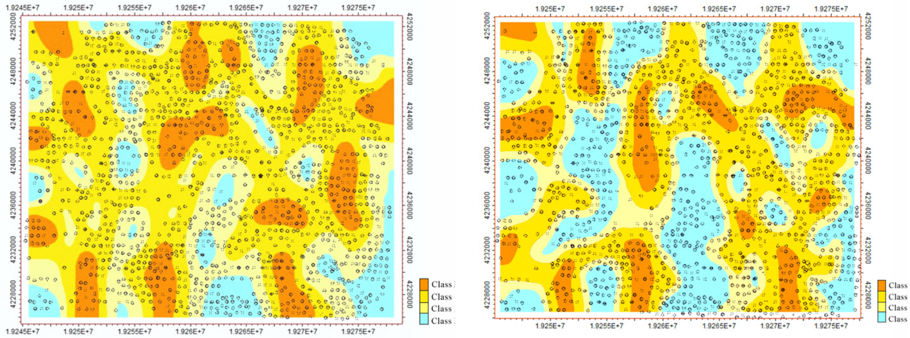
Fig. 1. Relationship between natural gas selling price and ultimate recovery rate of gas wells

Table 4. Classification evaluation standard table for reserves in the study area

Type	Sedimentary Phase	Sand Thickness	Effective Thickness (m)	Porosity (%)	Permeability ($10^{-3}\mu m^2$)	Saturation of Gas(%)	Abundance ($10^8 m^3$/km^2)	EUR ($10^4 m^3$)	Economic Rate of Return (%)
I	Development of a vertically layered, multi-phase deltaic distributary channel	large in scale, strong continuity.	>4	>10	>1.0	>70	>1.38	>1490	>8

II	The delta has well-developed distributary channels and multiple vertical stages.	relatively thick, relatively large in scale, continuity	2~4	8~10	0.8~1.0	60~70	1.33~1.38	1320~1490	6~8
III	Poor development of distributary channels and poor vertical multi-stage development	small in scale, Thin, discontinuous	1~2	6~8	0.5~0.8	50~60	1.28~1.33	1170~1320	0~6
IV			<1	<6	<0.5	<50	<1.28	<1170	<0

As shown in Figure 2, the classification of reserves is controlled by the sedimentary facies of the study area, and in some areas, it varies due to differences in reservoir heterogeneity. Among them, reserves in Categories II are distributed in large contiguous areas, accounting for more than 90% of the reserves, while reserves in Categories III and IV are sparsely distributed (Table 5).



(a) H8 (b) S1

Fig. 2. Classification map of reserves in the study area

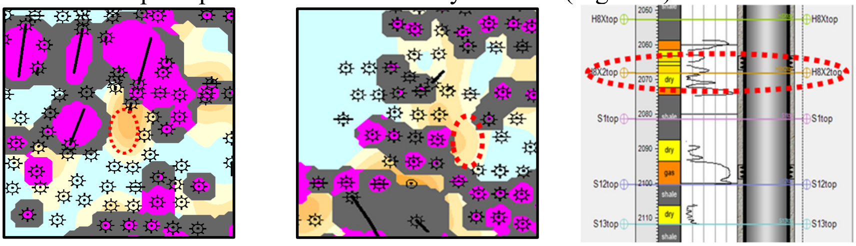
Table 5. Distribution of various types of reserves in the study area

Reserve Type	Surface Area Containing Gas (km^2)	Average Abundance (10^8/km^2)	Reserves (10^8m^3)	Proportion (%)
I	398.32	1.76	700.13	53.68
II	353.45	1.38	488.69	37.47
Subtotal: I+II	751.77	1.58	1188.82	91.15
III	67.39	1.32	88.95	6.82
IV	23.78	1.12	26.56	2.03
Total	842.94	1.55	1304.33	100.00

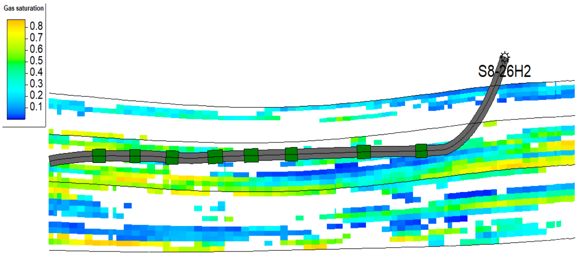
5 Distribution of Remaining Available Reserves

5.1 Classification of Remaining Available Reserves

The comprehensive study of the distribution of geological reserves in the horizontal and vertical directions divides the remaining reserves in the study area into an uncontrolled well network area and a complex sand body edge area on the horizontal plane; the remaining reserves are divided into isolated sand bodies with thin lost layers and areas with incomplete perforations between layers[5,13,14] (Figure 3).



(a)uncontrolled area of well network (b)composite sand edge area (c)incomplete perforation area



(d)Thin-layer isolated sand reserves

Fig. 3. Classification of remaining available reserves

5.2 Distribution of Remaining Available Reserves

Unconstrained reserves in the current 500 × 600 m well network refer to the reserves unaffected by the gas wells in the network. The degree of well network perfection can be improved by deploying infill wells. These reserves are the remaining recoverable reserves (Figures 4 and 5). The uncontrolled reserves in the H8 well network in the box are about 31.189 × $10^8 m^3$, accounting for 49.39%, and the uncontrolled reserves between the wells in the S1 of the mountain are about 22.597 × $10^8 m^3$, accounting for 58.58%.

Incomplete perforation reserves refer to the remaining gas that has not been fractured and perforated due to the limitations of early development of vertical well multi-layer fracturing technology or due to the thin thickness and poor physical properties of some gas-bearing formations. It has the characteristics of a small single-layer thickness. The H8 is approximately 8.606 × $10^8 m^3$, and the S1 is approximately 8.405 × $10^8 m^3$.

Composite riverbank edge reserves refer to effective gas layers that cannot be communicated by fracking. These reserves are relatively scattered, and it is generally not feasible to deploy production wells as a whole. These reserves and the 8th layer contain approximately $22.911 \times 10^8 m^3$, while the 1st layer contains approximately $7.456 \times 10^8 m^3$.

Thin-layer isolated sand reserves refer to isolated sand bodies omitted in the well network deployment. Usually, the thickness of the sand body is less than 2m, and it is distributed discontinuously in a thin sheet. Such reserves amount to about $437 \times 10^8 m^3$ for H8 and $119 \times 10^8 m^3$ for S1.

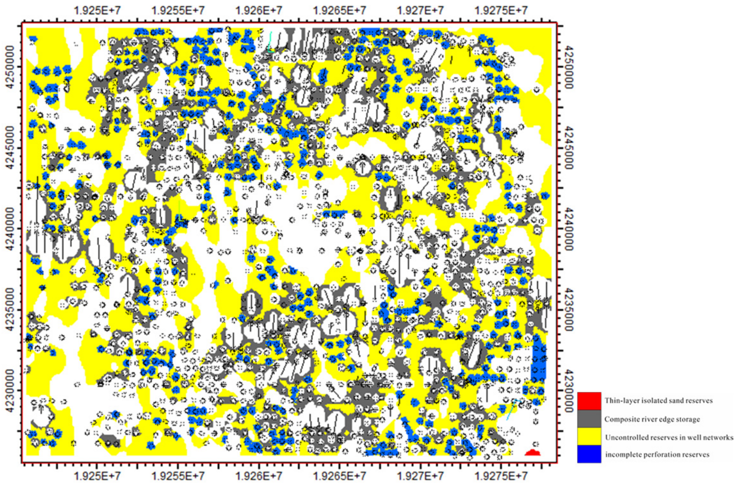


Fig. 4. Distribution of remaining available reserves for H8

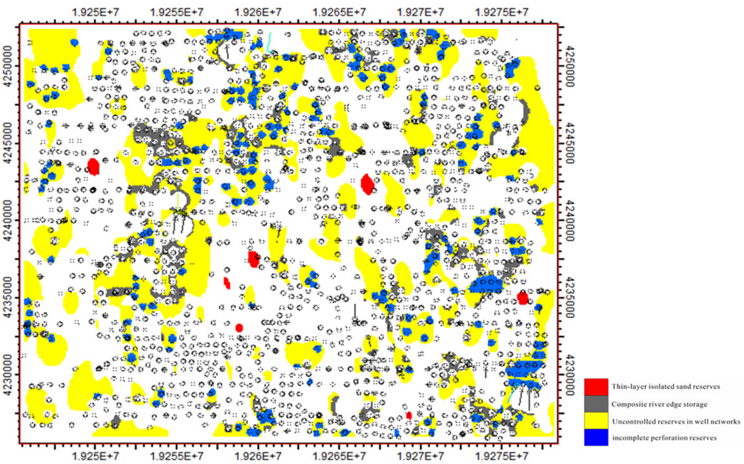


Fig. 5. Distribution of remaining available reserves for S1

5.3 Steady Production and Tapping Potential Measures

Based on the remaining gas control factors, distribution laws, and the degree of well network control, with the goal of cost-effective production and enhanced recovery, priority is given to mobilizing the $53.786 \times 10^8 m^3$ of uncontrolled reserves in the well network. The tapping of remaining reserves between wells is mainly carried out by deploying new wells and horizontal well expansion, among which new wells are deployed by drilling new conventional vertical/directional wells and conventional horizontal wells or fully utilizing the cost advantages of old wells and sidetracking[15,16]. Regarding the causes and distribution of remaining gas between layers, the deployment of double horizontal wells is adopted to tap the remaining reserves of superimposed sand bodies in multiple layers. In contrast, layer investigation and hole filling tap the remaining reserves of secondary productive layers.

6 Conclusion

(1) The geological reserves in the study area were calculated using the volume method as the main method and the geological modeling method as the supplementary method, which corroborated each other, and the geological reserves in the study area were calculated to be 1304.33×10^8 m^3. The reserves are mainly distributed in $H8_2$ and S1, with fewer reserves in $H8_1$. The average abundance of reserves is 1.49×10^8 m^3/km^2.

(2) A reserve classification and evaluation system with the internal rate of return as the core is constructed, and the geological reserves are divided into four categories: I, II, III, and IV. The distribution is controlled by the distribution of sedimentary facies and the macroscopic heterogeneity of the reservoir.

(3) There are four remaining recoverable reserves: uncontrolled well network areas, complex sand body marginal areas, isolated sand bodies with thin lost layers, and areas with incomplete perforations. Uncontrolled well network reserves are the mainstay of remaining recoverable reserves, accounting for 49.39% of the H8 and 58.58% of the S1.

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