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Feasibility Study and Parameter Optimization of CO_2 Injection Technology in Heavy Oil Field#

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ABSTRACT

CO_2 injection technology is a widely used extraction method for conventional and unconventional oil reservoirs. This technology can further achieve carbon sequestration and carbon neutrality on the basis of improving recovery efficiency. Under the guidance of the above ideas, firstly, theoretical methods are used to analyze the feasibility of various CO_2 injection technologies. Among the composite CO_2 technologies, CO_2 flooding after CO_2 huff-n-puff has better applicability compared to other technologies. Secondly, numerical simulation methods are used to optimize the technical scheme design of the block. After optimizing the parameters of single factor gas injection, conventional gas injection, mixed gas injection, water gas alternation and other injection methods are optimized. The results show that the optimal single factor CO_2 injection scheme can increase the final recovery rate by 13 percentage points compared to water drive; The water to CO_2 ratio is 1:1, and injecting water to air circulation in a 3-month cycle can achieve optimal results. In the current context of carbon neutrality, the scale of CO_2 injection applications will continue to expand, and this research will also provide technical support for the promotion and application of CO_2 injection technology.

Keywords: CCUS, CO_2 composite injection technology, heavy oil reservoir, field application, enhanced oil recovery

1. INTRODUCTION

CO_2 injection technology is currently one of the important techniques for improving oil recovery, which has the advantages of good effectiveness, fast results, economic and environmental protection, and wide applicability. It is widely used in various types of reservoirs such as low-permeability tight, fractured, carbonate rock, shale, and complex fault blocks. It is also widely used in heavy oil reservoirs (SAYEGH S G,1984; WEI B,2019). China has abundant heavy oil resources (Figure 1), ranking fourth among the world's heavy oil producing countries, only behind the United States, Canada, and Venezuela. Currently, more than 70 heavy oil fields have been discovered in 12 basins, with enormous development potential. Due to the special composition of its physical properties, heavy oil has characteristics such as high viscosity and poor flowability, but it also exhibits higher temperature sensitivity. Therefore, steam injection thermal recovery is currently a more conventional and effective extraction method. However, with the increasing difficulty and cost of extraction, diversified development models have gradually emerged on the stage. The proposal of CO_2 injection technology provides a theoretical basis for solving the problem of improving heavy oil recovery (Yuan Shiyi,2018; JIA Ruixuan,2020; LIU Z,2019). After CO_2 dissolves in crude oil, it can not only effectively reduce its viscosity and greatly improve its fluidity(Makimura, D,2013; Guan Wenlong,2023; G C Bank,2007), but also increase the elastic energy of the formation through the volume expansion of crude oil (Wang Q,2019; WELKER J,1963),thereby reducing residual oil saturation and improving oil displacement efficiency. Long term CO_2 injection into the formation can effectively store it underground, which is a scientific means to achieve carbon neutrality and reduce carbon emissions (JHA K,1986; MOHAMMED-SINGH L,2007).

2. CURRENT STATUS OF GAS INJECTION TECHNOLOGY RESEARCH

2.1 *Practice of Gas Injection Technology in Fields*

A The Yates oil field in the United States initially adopted natural energy development methods, but later

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switched to nitrogen injection technology for production. Based on the characteristics of the target heavy oil reservoir, steam injection technology was later used to reduce crude oil viscosity and effectively improve the recovery rate.

The Buena Vista oil field and Iberia oil field in the United States both adopt the technology of top injection of natural gas after water flooding to enhance oil recovery. Through the formation of a secondary gas cap, the injected gas can be linked with the crude oil in the pores of carbonate reservoirs under gravity differentiation, and the remaining oil retained at the top of the structure after the well water is flooded is extracted. The recovery rate of Buena Vista oilfield has increased by nearly 10% compared to water flooding, and it is estimated that the recovery rate of Iberia oilfield can be increased by about 13%, with a significant increase in production effect.

The Bati Raman fractured carbonate oil field in eastern Türkiye with CO_2 huff and puff technology, and the daily average oil production of a single well increased by 60%, while the recovery factor increased by 5.0 percentage points. This practice has shown that one of the important mechanisms for increasing production in fractured carbonate reservoirs using this technology is the diffusion of CO_2 gas within the matrix fracture system.

The Ngaylengyel oil field is located in southern Hungary and has undergone early water flooding, resulting in extremely high water content and low gas oil ratio. To address the aforementioned issues, a gas drive pilot test was conducted by injecting a large amount of CO_2 to form an artificial gas cap. Under the multiple effects of gas cap expansion and gravity, the attic oil in caves and cracks was effectively extracted, with a recovery rate increase of nearly 10%.

Tahe Oilfield is the earliest discovered carbonate reservoir with representative significance in China. After early water injection development, the production decreased rapidly and faced the problem of high water content in oil wells. Gas injection development has become an effective measure to solve the above problems. Indoor experiments and field practices have confirmed that injecting N_2 or CO_2 can achieve good production increase effects. Injecting gas can not only reduce viscosity and increase energy, but also utilize gravity differentiation to better extract crude oil.*Section of Introduction.*

Carbon dioxide capture, utilization, and sequestr ation (CCUS) is to capture and purify CO_2 from ind ustrial emitters, utilize such captured CO_2 for other purposes (e.g., directly injecting it into geological fo rmations) and then store it in a subsurface reservo ir permanently. In practice, injecting CO_2 into an oi l/gas reservoir can increase production and enhanc e oil/gas recovery, allowing us to store CO_2 in the reservoir once depleted. Due to its unique physical and chemical properties, CO_2 may exist as a gaseo us phase, be dissolved in the oil and/or water, an d react with rock matrix as a mineralized solid pha se, among which the latter is considered as a stabl e form of carbon sequestration.

Table 1. Gas injection case of carbonate reservoir

Reservoir name	*Development method*	*Gas injection medium*
Yates Oilfield	Inject N_2 after depleted development	N_2
Buena Vista and Iberia oil fields	*Injecting natural gas after water flooding*	GAS
Ngaylengyel oilfield	CO_2 *flooding after water flooding*	CO_2
tahe oilfield	*Switching from water drive to gas drive*	CO_2/N_2
Bati Raman Oilfield	CO_2 huff-*n*-puff after water flooding	CO_2

2.2 Principles and Problems of Composite CO_2 *Injection Technology*

After the concept of gas injection technology was proposed, many scholars at home and abroad have studied its mechanism for improving oil recovery. The mechanism of gas injection to increase production mainly includes: reducing viscosity to improve crude oil flowability and expanding to increase energy; Reduce resistance during gas displacement/throughput process by lowering surface tension; Extracting light hydrocarbons to improve the utilization of remaining oil; Change wettability to reduce residual oil saturation; Internal dissolved gas drive drives the flow of crude oil, etc.

When the viscosity of the crude oil in the reservoir is high, we can adopt the composite technology of viscosity reducer+CO_2. Viscosity reducers can reduce the viscosity of crude oil, making it easier for gas to enter the formation pores. The carrying effect of gas can allow viscosity reducers to enter deep into the oil reservoir, expanding their coverage.

CO_2 and N_2 combined throughput is one of the effective methods to improve the recovery rate of heavy oil reservoirs. CO_2 has excellent expansion and viscosity reduction as well as light hydrocarbon extraction effects. N_2 has a wide range of sources, high economic benefits, and stable performance. It has significant effects on energy enhancement, drainage assistance, and gravity drive, and can effectively solve problems such as wellbore corrosion.

In foam gas injection technology, foam has good plugging performance. Through effective plugging of fractures and high permeability strips, more gas can enter low permeability reservoirs, and the sweep efficiency of injected fluid can be improved. At the same time, the injected surfactant has excellent properties of changing wettability and reducing surface tension, which can effectively extract heavier components from hydrocarbons and improve yield enhancement. But when applied in oil reservoirs, it has to face challenging issues such as wettability, interfacial tension, and extremely low permeability. Compared to surfactants with ultra-low interfacial tension and wettability, good foaming surfactants do not alter wettability or achieve low interfacial tension

In nano gas injection technology, due to the small specific surface area of the injected nanoparticles and the fact that nanoparticles can play the main role at low concentrations, and the nano system can better penetrate the pore medium, it is beneficial to drive the crude oil in the nano pores, thereby improving the recovery rate and gradually being applied in the field of oil and gas reservoir development. It is worth noting that nanoparticles are not easily stable under special conditions, and most organic media are expensive. Therefore, the stability of nanoparticles and the cost of use must be taken into account. We hope that nanofluids have the ideal advantages of high economy, small particle diameter, and stable properties.

3. MATERIAL AND METHODS

3.1 *Overview of oil reservoirs and establishment of numerical simulation models*

The target reservoir is buried at a depth of 1324-1350m; The porosity is 33% and the permeability is 1893 $\times 10^{-3}$ μ m, belonging to a high porosity high permeability reservoir. Through artificial water flooding and bottom water energy development, it has gone through three stages: natural energy development, water injection development, and carbon dioxide injection development. Currently, the carbon dioxide injection stage is underway.

By adjusting the regression variables of the fluid, the fitting accuracy of indoor PVT experimental data can be further improved, and relevant critical parameters reflecting the actual properties of the formation fluid can be obtained to establish a reservoir fluid model. Reservoir permeability ranging from 1000mD to 3000mD; The porosity range is between 26.8% and 33.2%, and a numerical simulation model of the reservoir with a grid size of 39 × 30 × 7 is established. The planar grid size is 60m × 60m, including 4 production wells and 1 injection well. The intercepted area is 0.46km^2, with an average oil layer thickness of 6.6m, porosity of 0.33, and oil saturation of 0.6.

4. RESULTS AND DISCUSSION

4.1 *The influence of injection and production parameters on recovery rate in heavy oil reservoirs*

By establishing a numerical simulation model, CO_2 composite gas drive parameters were optimized for the target block. Firstly, single factor optimization was used to optimize the parameters of injection volume, bottomhole flowing pressure, and shut in gas oil ratio. The daily injection volume range was 30-55 t, bottomhole flowing pressure range was 2-11 MPa, and shut in gas oil ratio range was 500-3000; At the same time, a variance analysis was conducted on the results of the multi factor orthogonal experiment using recovery rate as the indicator to obtain the order of the impact of each parameter on the development effect. Finally, a scheme design was carried out for water gas alternation, with a water gas ratio range of 1:3-3:1 and other parameters unchanged. The influence of various composite injection methods on the development effect of the reservoir was analyzed and evaluated. And provide decision-making solutions with different weights according to the developer's needs.

On the one hand, the daily injection volume affects the injection pressure during gas injection, and on the other hand, it also affects the production cost of CO_2 composite flooding. When the daily injection volume is 40-45t, the recovery rate basically reaches the maximum value of 37%. When the daily injection volume is too large, it will cause the CO_2 migration speed to be too fast, reduce the contact time with the formation crude oil, and thus reduce the effect of crude oil viscosity reduction and expansion. Considering the production increase effect and economic benefits, the optimal daily injection volume should be 40-45t.

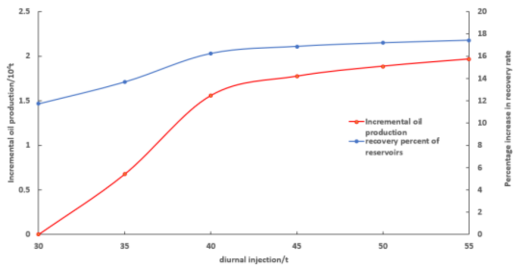

Fig. 1 Oil field production increase effect under different daily injection rates

Optimization of bottomhole flow pressure can ensure the oil production capacity of the production well within a reasonable range, as well as maintain the pressure level of the formation to ensure the supply of formation energy. When the bottom hole flowing pressure of the production well exceeds 10MPa, there is a significant fluctuation in the decrease in recovery degree. This is because when the bottom hole flowing pressure is too high, the pressure difference in the reservoir production process becomes smaller, and when it exceeds the critical point, it is not enough to maintain the target oil production rate, resulting in a decrease in development efficiency. Therefore, 10MPa is selected as the optimal bottom hole flowing pressure.

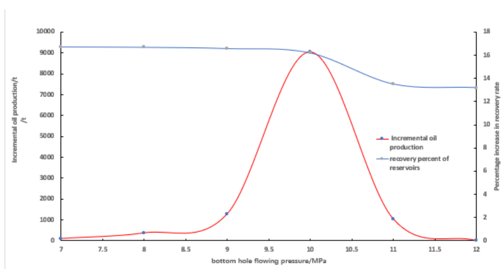

Fig. 2 Oil field production increase effect under different bottomhole flow pressures

4.2 *T Optimization of* CO_2 *composite gas drive injection method*

Firstly, the effectiveness of four development methods, including full gas injection, top gas injection and bottom water injection, top water injection and bottom gas injection, and individual bottom gas injection, was demonstrated through mechanism model analysis. By comparing the recovery rates of different development methods, the preferred order of the four methods is: full gas injection>top gas injection and bottom water injection>individual bottom gas injection>top water injection and bottom gas injection. The final recovery rate of full gas injection is 1.28 percentage points higher than that of top water injection and bottom gas injection. The development effects of

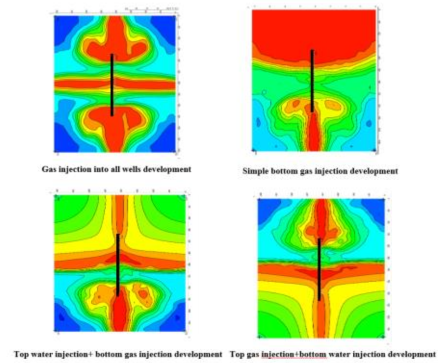

Fig. 3 Comparison of the effects of different development methods

the four methods are shown in Figure 3.Conclusions.

The application of water gas alternation technology can control production costs on the one hand, and on the other hand, alternating injection avoids the risk of early gas breakthrough compared to long-term injection of a single gas, which is more conducive to improving recovery efficiency. Analysis was conducted on five sets of simulation experiments with gas water ratios of 1:3, 1:2, 1:1, 2:1, and 3:1. The results in Figure 6 show that when the gas water ratio is lower than 1:3, the recovery degree is positively correlated with the water injection volume, with an increase in recovery percentage points of 8.21, 16.86, 17.59, 17.86, and 18.19, respectively. As the water injection ratio increases, the recovery degree shows a trend of first increasing and then flattening. The inflection point is at a gas water ratio of 1:1, so the preferred water gas ratio is 1:1.

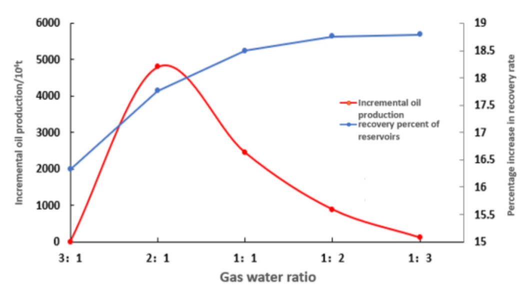

Fig. 4 Oil field production increase effect under different gas water ratios

This is because when the gas to water ratio is too high, the injected water is difficult to effectively suppress the formation of CO_2 gas channeling, and premature gas channeling leads to a decrease in recovery rate. However, when the water to water ratio is appropriate, on the one hand, it can increase the gas sweep volume and fully utilize the viscosity reduction and expansion energy enhancement effects of CO_2 in crude oil. On the other hand, the injected water can effectively suppress the channeling of CO_2 gas and improve the gas displacement efficiency.

5. CONLUSION

Analysis of domestic and foreign mine experiments shows that CO_2 injection technology is an efficient, economical, environmentally friendly, and widely applicable technology for improving oil recovery. At present, CO_2 composite gas drive technology has been widely used in various types of oil reservoirs such as heavy oil, tight oil, and fault blocks, providing new ideas for the development of heavy oil reservoirs.

When the proportion of CO_2 in the mixed gas is about 80%, the recovery degree is close to the peak, which can fully utilize the effects of CO_2 viscosity reduction and expansion energy enhancement, and correspondingly reduce investment costs; When water gas alternation occurs, the preferred gas water ratio is 1:1. On the one hand, it can use water plugs to suppress premature breakthrough of CO_2 gas and expand the affected volume. On the other hand, it avoids frequent gas water alternation measures and reduces construction difficulty.

In the discussion of composite gas drive technology for heavy oil reservoirs, the application of more methods such as composite huff and puff technology, viscosity reducer solution gas alternation technology, foam composite gas drive, and nano gas injection technology provides ideas for dealing with complex situations under different geological conditions.

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