Sustainable Strategy for Gas Supply in China: Based on Foam Drainage Gas Recovery Technology

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Abstract

With the increasing demand of natural gas in China, its production is extremely important to fulfill the requirement of society. However, in reality, the natural gas production from the gas well in the gas field is often accompanied by the production of formation water. For gas well with low production, the gas flow rate in the well is too low to carry out the formation water from the bottom of the well. The water will thus accumulate in the well bore and the gas production will be greatly diminished. To solve this problem, based on the developing status of M gas field in China, foaming surfactant Z301 is synthesized and then foaming agent ZK3012 is developed through combination of Z301 with CAT after optimization experiments. After

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that, the compatibility tests are conducted to ensure that ZK3012 can work together well with formation fluids, and the water carrying rate tests are conducted concerning the optimum concentration of ZK3012. Finally, pilot test is conducted in 2 gas wells on site in M gas field, good results are obtained that accumulated water is discharged by foam drainage and the gas well production is increased. Studies demonstrate the main steps involved for application of this technology. In regard to the high external dependence degree of China in gas supply, operators of gas fields should give prominence to related studies of this technology to achieve sustainable development.

Keywords: Field test, foam drainage, low production, gas well, enhanced oil recovery.

1 Introduction

Under the background of complex epidemic situation, promoting sustainable development through technological progress is an important issue that needs to be consistently explored. Many scholars have put forward good schemes concerning this issue from their own professional point of view. Xie et al. built a simulation model by Matlab/Simulink software concerning the synergic action of electric transmission system with new energy vehicle, analyzed the influence of detailed factors, and finally proposed a reliable motor optimization scheme for improving the efficiency of electric transmission systems [1]. Deng et al. studied the electrochemical dechlorination from Trichloroethylene (TCE), and Manganese phthalocyanine (MnPc) is recommended in this process as the catalyst. After detailed analysis of different parameters, this method is found to be an effective way with great potential of large-scale application for the remediation of TCE-contaminated groundwater [2]. Such studies as these will definitely play positive reference roles for decision makers concerning the making of sustainable development policies all over the world.

Since the establishment of reform and opening up policy, China has experienced a process of rapid economic development and thus made some progress in many aspects. At the same time, along with the development process, China also encountered a series of problems, and its sustainable development is facing enormous challenges. To take the road of sustainable development in economics, society and ecology, China must vigorously develop and apply new technologies to solve the problems encountered in the process of progress. To be specific, it can start from two aspects: one is to study the trends and characteristics of contemporary technological innovation worldwide, and learn how to use specific technological innovation to promote sustainable development; the other is to study the effects of technological change in contemporary developed countries, and learn how to achieve new growth through new technological breakthroughs.

From the view of energy supply, this paper first analyzes the trend of natural gas import in China, clarifies the fact that China's natural gas supply is self-insufficient. Then, based on a cooperation project with oilfield, concerning the exploitation of natural gas, some technical essentials are raised step by step in detail concerning the technology application of foam drainage gas recovery. It aims to provide development suggestions for promoting the sustainable supply of natural gas in China through the promotion and application of new technologies.

Foam is usually used for oil displacement purpose in the development of oil field. This is mainly because foam can have the unique advantage of profile control which is important for enlarged swept volume in the enhanced oil recovery process. Many scholars have made lots of studies concerning the application of foam flooding. Spontaneous generated foam flooding technology does not require special gas supply and injection equipment and is relatively easy for application on site. By model experiment, Pu et al. studied the oil displacement mechanism of authigenic CO_2 foam complex system, which lays a foundation for the further study for the application of this technology [3]. Liu et al. analyzed the stability, rheology and percolation characteristics of nitrogen foam in porous media, summarized the mechanism and injection mode of nitrogen foam flooding, and proposed the new research direction for the problems existing in the development of nitrogen foam flooding technology [4]. According to the characteristics of high temperature and high salinity in ZY oilfield, Zhao et al. screened out the foaming agent formula for air foam flooding, and proved the mechanism and special advantages of the air foam flooding through laboratory experiments [5]. Combining the foam system with the gel system, Li et al. proposed the composite nitrogen foam profile control technology, and analyzed the field control measures and implementation effect of the technology in combination with the field implementation process [6]. In view of the development status and technical requirements of Bohai Oilfield, in order to solve the problem of poor foam stability in the process of foam profile control, Kuai et al. evaluated and screened SiO_2 nanoparticles which can greatly enhance foam stability, analyzed their foam stabilization mechanism, and investigated the plugging effect and flow diversion ability of three-phase nano-foam system [7]. Wang et al. designed a measuring device for plugging and profile control of self-heating foam system, studied the plugging and profile control mechanism of self-heating foam system in seepage flow, and finally provided very specific conclusions [8]. Actually, foam can also be used in many other aspects for the oil and gas field development. Li et al. introduced the foaming agent for foam fluid and summarized the various applications of foam fluid in wellbore, including foam drilling, cementing, well control, flow inducing, well flushing, fluid drainage and so on [9]. Xue et al. carried out visualized microscopic experimental study on foam/gel water shutoff by using microscopic simulation model. The main formation mechanism of remaining oil in each development stage is characterized [10].

Actually, foam can also be used for carrying water out from the production well in gas field development, and many scholars have conducted research concerning this issue. Fan et al. summarized the research progress of nanoparticles as solid foam stabilizer in foam drainage gas recovery of China, and prospected the application prospect of nanoparticles in foam drainage technology [11]. By testing the law of throttling pressure drop and establishing or improving the mathematical model, Wang et al. effectively improved the downhole throttling design level of foam drainage wells [12]. Jiang et al. conducted comprehensive research on foam drainage gas recovery technology concerning the shale-gas platform wells and the shale gas development results have been greatly improved in the target research area [13]. Zhai et al. conducted study on smart foam drainage technology in cluster gas wells based on its application to Yanbei project. The economic performance of this technology is approved in this study and is suggested as a promising technology with great potential for enlarged application [14].

The main object in this study is actually a pilot test concerning the foam drainage gas recovery in M gas field. M gas field is located in the northwest region of China and most of its gas wells start to have low gas production rate of no more than 1×10^4 m^3 per day in recent 2–3 years. This rate is generally too low to carry water from the bottom of well and thus there will be water accumulating in the well bore which will be a great challenge for the steady production of gas. Under this circumstance, foam is used as the drainage agent for carrying water from the bottom to the mouth of the well.

Due to the high salinity of formation water, the foaming ability of foaming agents will be influenced and the foam drainage ability will be reduced. Based on the real problems on site in M gas field, new type foaming agent is developed with high-salinity resistivity. Pilot test is then carried on to evaluate the effect. Results show that the well-bore accumulated liquid can be discharged by the foam and the gas well production can be improved. This technique can be good reference for low-production gas well stimulation all over the world.

2 Gas Import Review of China

Based on the statistics of made by BP recently, a brief review of gas supply situation in China can be obtained [15].

Figure 1 below shows the pipeline imports of gas in China since year 2010 to year 2021. The data used in this Figure is obtained from BP [15]. The vertical coordinate uses a unit of billion cubic meters. From the curve, it is obvious that the trend is generally always in an increasing pattern. In the year 2010, the imported pipeline gas has a quantity of 3.4 billion cubic meters while this value has increased to 53.2 billion cubic meters in year 2021. There is only 1 short decreasing period: during the year 2018 to 2020. This trend may be somewhat influenced by bad effects of the corona virus.

The quantity of LNG imports in China is also demonstrated in the Figure (see Figure 2). The data used in this Figure is obtained from BP [15]. From the figure, it is clear that the imported quantity is always in the increasing pattern. Furthermore, the increasing speed actually become larger since the year 2015. In the year 2010, the imported LNG has a quantity of equivalent 13.0 billion cubic meters while this value has increased to 109.5 billion cubic

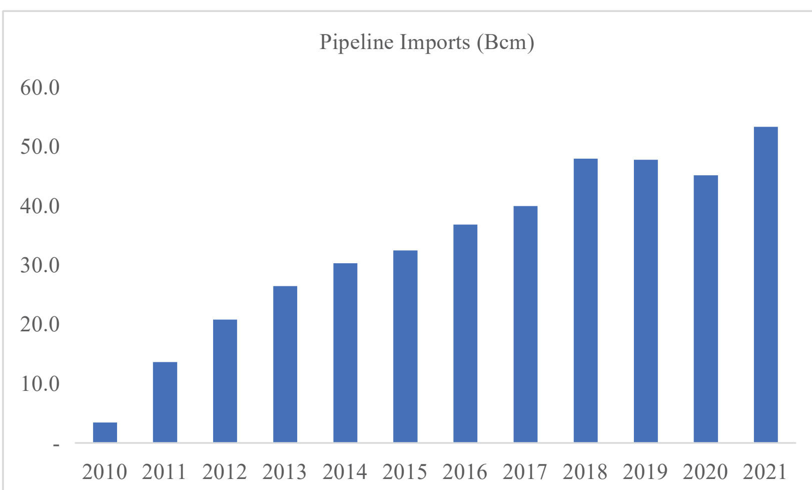

Figure 1 Pipeline imports of China in recent years (Bcm).

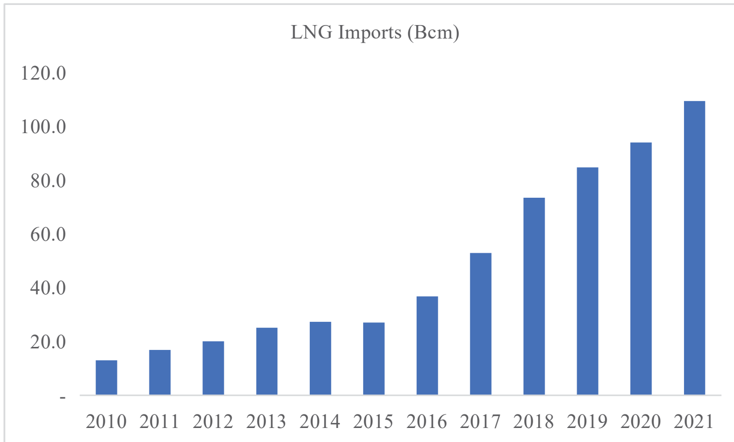

Figure 2 LNG imports of China in recent years (Bcm).

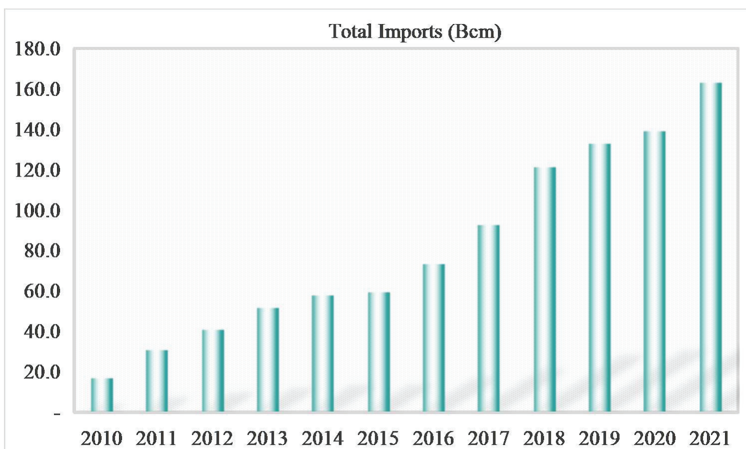

Figure 3 Total gas imports of China in recent years (Bcm).

meters in year 2021. There is only 1 short decreasing period: during the year 2014 to 2015. This trend may be influenced by the economic crisis at that time.

In order to see the gas imports as a whole, the quantity of total gas imports in China is also demonstrated in below figure. The data used in this Figure is obtained from BP [15]. From Figure 3, it is shown that the imported quantity is always in an increasing pattern. In the year 2010, the imported gas has a total quantity of equivalent 16.4 billion cubic meters while this value has increased to 162.7 billion cubic meters in year 2021. There is no decreasing period at all, which means that the external dependence of gas supply in China has always been increasing without any change. Therefore, it is of great challenge for operators of gas fields to ensure steady production of gas. New technologies have to be applied into the production process for better gas field operation. Only in this way, the sustainable supply of gas may be relatively easier to realize in China.

3 Development of Foaming Agent

3.1 Synthesis of Foaming Surfactant

The formation water salinity is of high value in the M gas field. This high salinity can influence foaming ability, so the screening of surfactant has to be paid more attention to. In this project, amphiphatic or nonionic type surfactant, active groups containing acetic acid or sulphonic acid which is not sensitive to electrolyte, are firstly chosen as the raw material for synthesis of foaming surfactant.

Based on theory above, the foaming surfactant Z301 is finally synthesized by raw components such as polyethylene glycol, perfluoro caprylic acid, phosphorous pentoxide, dimethyl propane diamine and so on. Performance test is then conducted for foaming surfactant Z301 to obtain the bubble height at different times, the liquid-carrying volume, the liquid-carrying time, and the liquid-carrying flow rate of corresponding foam generated. The detailed results are shown in Table 1 below.

Through analysis of experiment results, it is easy to see that the foaming surfactant Z301 synthesized has good properties for foam stabilization. However, the liquid-carrying abilities of foam is not very adequate, so more components are needed as supplementary agent which should play a positive role to improve the liquid-carrying ability of foam.

Table 1 Performance experiment of foaming surfactant Z301 synthesized

Content (%)	Bubble Height (mm)			Liquid-carrying Volume (mL)	Liquid-carrying Time(s)	Liquid-carrying Flow Rate (mL/s)
	0 min	5 min	10 min			
0.1	81	71	61	82.6	122	0.69
0.2	151	142	134	99.4	122	0.83
0.3	171	154	145	110.8	122	0.95
0.4	222	186	181	133.4	122	1.09

Source: Research findings.

Table 2 Foaming agent further development based on foaming surfactant Z301

	Foaming Agent Composition		Foam Property		
Item	CAT(L)	Surfactant Z301(L)	Initial Bubble Height (mm)	Bubble Height After 3 Minutes (mL)	Liquid Carrying Volume (mL)
1	0.50	0.25	225	315	216.7
2	0.75	0.25	255	350	227.7
3	1.00	0.25	235	315	214.5
4	1.25	0.25	165	215	196.9
5	1.60	0.25	170	110	176.9
6	1.60	0.25	150	80	156.8

Source: Research findings.

3.2 Optimization of Foaming Agent

Concerning the deficiency of foam generated by Z301 in liquid-carrying ability, more surfactant with low molecular weight is screened as supplementary components for final foaming agent. After many tests, CAT is finally chosen as the target mixing agent with Z301 which also has good compatibility.

To further identify the appropriate mixing portion between CAT and Z301, more experiments are carried on concerning the bubble height at different times and the liquid-carrying volume of foam. Detailed experiment results are demonstrated in Table 2 below.

As shown in Table 2, when the volume ratio of CAT with Z301 is 3:1, foam generated by this kind of mixture can have the largest bubble height and the liquid-carrying volume. Therefore, the foaming agent is finally synthesized in this proportion (CAT: Z301 = 3:1) as ZK3012.

4 Further Investigation of Foaming Agent ZK3012

4.1 Laboratory Experiment

In order to verify the compatibility of ZK3012 in real high salinity situations, the water sample form well M8001 and M8002 are used as the solvent for further experiment. Totally 10 experiments are conducted to identify the appropriate concentration of foaming agent ZK3012.

The experiments are conducted with total liquid volume of 250 ml under temperature 65∼70°C, and the gas flow rate is 780 mL/min in the dynamic liquid carrying experiment. The experiment results are mainly about the liquid-carrying rate at different ZK3012 concentration and the details are shown in Figures 1 and 2 below. Actually, based on field experiences, to

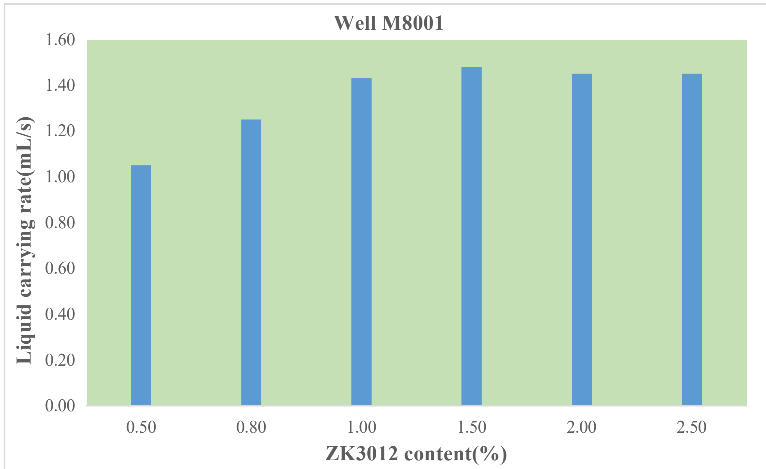

Figure 4 Liquid carrying rate based on different ZK3012 concentrations in well M8001 water.

ensure a good water-carrying effect, the liquid-carrying rate should be no less than 1.37 mL/s in the laboratory experiment.

As demonstrated in Figure 4 concerning water sample from well M8002 as the solvent, the liquid carrying rate of foam increases from the beginning when ZK3012 concentration starts to increase. The best liquid carrying rate is obtained at 1.48 mL/s when ZK3012 concentration is 1.5%. After that, the liquid carrying rate starts to decrease when ZK3012 content further increases.

As demonstrated in Figure 5 concerning water samples from well M8002 as the solvent, the liquid carrying rate of foam increases from the beginning when ZK3012 content starts to increase. The best liquid carrying rate is obtained at 1.50 mL/s when ZK3012 concentration is 2.0%. After that, the liquid carrying rate starts to decrease when ZK3012 content further increases.

Based on experiment and analysis above, the foaming agent can generally be confirmed as effective. Its main properties are also tested and the results are shown in Table 3 below.

4.2 Compatibility Experiment

Series of compatibility experiments are conducted to check whether ZK3012 can work well with various fluids in reservoir.

The first experiment is about the compatibility between ZK3012 and fluids with different salinity. The concentration of ZK3012 is 3% and the

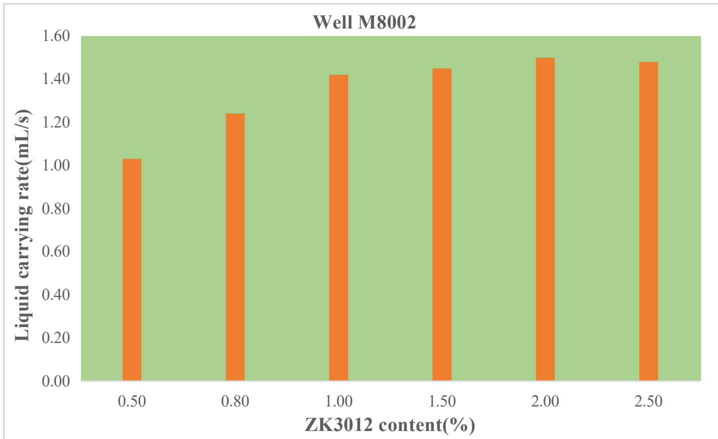

Figure 5 Liquid carrying rate based on different ZK3012 concentrations in well M8002 water.

Table 3 Performance index of foaming agent ZK3012

Item		Index
pH Value (20°C)		7.0∼8.0
Super-facial Tension (3‰ solvent, 20°C), mN/m≤		35.0
Density (20°C), g/cm^3		1.0∼1.05
Range of application	Temperature °C	≤120
	Salinity, 10^4 mg/L	0∼20

Source: Research findings.

Table 4 Compatibility experiment with fluids of different salinity

Salinity (10^4 mg/L)	0.0	2.4	5.2	7.8	10.2
Results	no precipitation	no precipitation	no precipitation	no precipitation	no precipitation

Source: Research findings.

experimental temperature is 65∼70°C. The solution is laid aside for no less than 8 hours to find out whether there will be precipitation generated. Detailed results are as illustrated in Table 4. It is obvious that ZK3012 can keep a steady state without precipitation in a wide range of salinity.

The second experiment is about the compatibility between ZK3012 and condensate oil. The solution is composed of ZK3012, condensate oil and water. The concentration of ZK3012 is 3% and the experimental temperature is 65∼70°C. The solution is laid aside for no less than 8 hours to find out whether there will be precipitation generated. Detailed results are as

Table 5 Compatibility test with condensate oil of different concentration

Content of Condensate Oil (%)	5	12	18	22	25
Results	no precipitation	no precipitation	no precipitation	no precipitation	no precipitation

Source: Research findings.

Table 6 Compatibility experiment with formation water from well M8001

Content of Foaming Agent (%)	0.5	1.0	1.6	2.2	3.0
Results	no precipitation	no precipitation	no precipitation	no precipitation	no precipitation

Source: Research findings.

Table 7 Compatibility experiment with formation water from well M8002

Content of Foaming Agent (%)	0.5	1.0	1.6	2.2	3.0
Results	no precipitation	no precipitation	no precipitation	no precipitation	no precipitation

Source: Research findings.

illustrated in Table 5. It is obvious that ZK3012 can keep a steady state without precipitation in a wide range of condensate oil concentration.

The third experiment is about the compatibility between ZK3012 and formation water from well M8001. The experimental temperature is 65∼70°C and the solution is laid aside for no less than 8 hours to find out whether there will be precipitation generated. Detailed results are as illustrated in Table 6. It is obvious that ZK3012 can keep a steady state without precipitation in a wide range of concentration from 0.5% to 3.0%.

The fourth experiment is about the compatibility between ZK3012 and formation water from well M8002. The experimental temperature is 65∼70°C and the solution is laid aside for no less than 8 hours to find out whether there will be precipitation generated. Detailed results are as illustrated in Table 7. It is obvious that ZK3012 can keep a steady state without precipitation in a wide range of concentration from 0.5% to 3.0%.

4.3 Filling Quantity

Based on previous production experiences on site, the foaming agent quantity needed in pilot test can be calculated by formula below:

$$V = Q_{BL} \times C \times S \tag{1}$$

In the formula, V is the foaming agent quantity required for drainage; Q_{BL} is the liquid accumulated at the bottom of the well; C is the concentration of foaming agent; S is the intensity of liquid drainage.

5 Pilot Test

Take the production status and technical characteristics of gas wells into consideration, two gas wells are selected to commerce the foam drainage pilot test. The fundamental data for two wells are illustrated as Table 8.

Actually, for each well, 3 periods are chosen to add the foam agent solvents. Each period will last for about 5–10 days and the duration between 2 periods are about 10–15 days.

After filling the required quantity of foaming agent solvent mixtures into the well, positive results are obtained and detailed parameters are as Table 9.

Specifically, as for well M8001, its pressure distribution in well bore is improved and the pressure gradient at the lower part of well bore decreased.

Table 8 Fundamental data from 2 test wells

Well	Oil Pressure (MPa)	Casing Pressure (MPa)	Pressure Difference (MPa)	Minimum Liquid-carrying Quantity (10^4 m^3/d)
M8001	11.7	14.1	2.4	1.16
M8002	7.5	10.3	2.8	1.18
Well	**Gas Production ($10^4 m^3$/d)**	**Liquid Production (m^3/d)**	**Well-bore Liquid Stored (L)**	**Salinity (mg/L)**
M8001	1.10	0.24	837	48761
M8002	1.12	0.31	888	76284

Source: Research findings.

Table 9 Test and results about 2 test wells

Well	Time	Before Test (MPa) Oil Pressure	Before Test (MPa) Casing Pressure	After Test (MPa) Oil Pressure	After Test (MPa) Casing Pressure	Gas Production (10^4 m^3/d)	Liquid Production (m^3/d) Before Test	Liquid Production (m^3/d) After Test	ZK3012 Content (%)
M8001	1	11.7	14.1	13.1	13.7	1.1	0.24	1.00	2
	2	10. 2	12.8	10.7	10.9	1.1	0.32	0.80	2
	3	11.8	13.0	11.3	11.9	1.1	0.26	0.76	2
M8002	1	7.5	10.3	10.1	10.5	1.1	0.31	0.56	2.2
	2	8.7	10.5	10.1	10.5	1.1	0.11	0.67	2.2
	3	8.1	9.9	9.5	9.9	1.1	0.21	0.60	2.2

Source: Research findings.

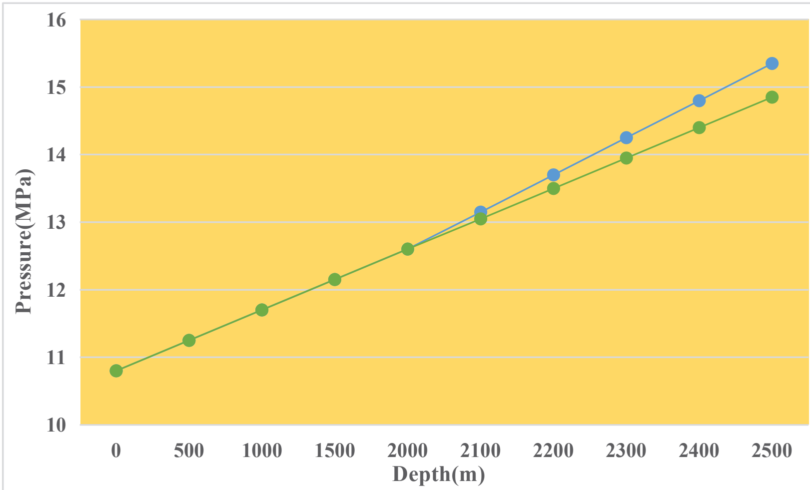

Figure 6 Pressure gradient before and after foam drainage in Well M8001.

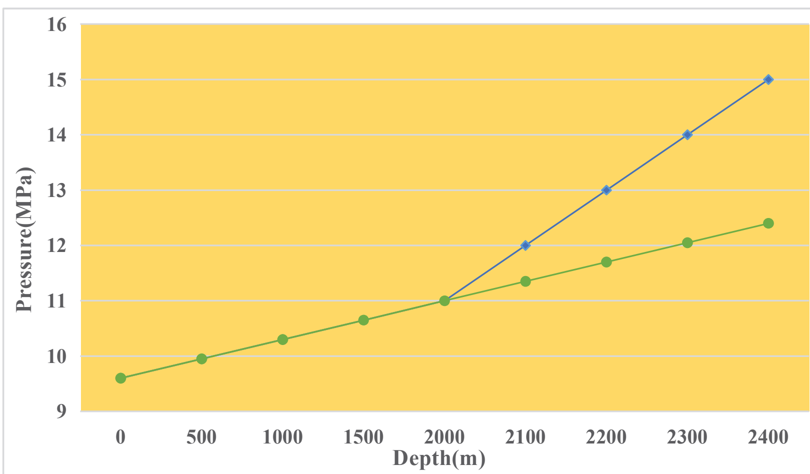

Figure 7 Pressure gradient before and after foam drainage in Well M8002.

This is because the water at the bottom of well are carried out and the density of well-bore liquid is thus diminished, see Figure 6. The gas production is increased by 29.3×10^4 m^3 during the testing period.

For well M8002, its pressure distribution in well bore is also improved and the pressure gradient at the lower part of well bore decreased. This is because the water at the bottom of well are carried out and the density of well-bore liquid is thus diminished, see Figure 7. The gas production is increased by 57.8×10^4 m^3 during the testing period.

6 Conclusion

Bottom hole liquid accumulation is a common problem in the middle and late stages of gas well production, and drainage gas recovery technology measures should be taken as soon as possible, while foam drainage gas recovery technology has the characteristics of low cost, quick effect, green environmental protection and so on, which can effectively guarantee the stable production of gas wells.

For application of this technology on site, based on screening of foaming surfactant Z301 and CAT, foaming agent ZK3012 is developed and optimized with series of experiments, including compatibility experiments of ZK3012 at different concentration with fluids of different salinity, with condensate oil, with formation water from Well M8001 and Well M8002. ZK3012 showed good properties concerning these compatibility tests and is primarily proved to be an effective foaming agent. After that, the filling quantity of foaming agent is also discussed with a formula being provided to reasonably calculate the required quantity for pilot test on site. Finally, based on a cooperation project with M gas field in China, field pilot test is carried on in 2 gas wells and good results are obtained. The difference between oil pressure and casing pressure is largely reduced and both the gas production as well as liquid production are increased. Pressure distribution in well bore are also improved both in Well M8001 and Well M8002 and the pressure gradient at the lower part of well bores decreased, suggesting that the liquid accumulated is carried out effectively by foam. Studies show that foam drainage gas recovery technique is of great prospect for effective and steady gas production.

In fact, this technology can be further optimized in many aspects to improve its application effects: (1) In view of the characteristics of liquid accumulation in gas wells, technicians should comprehensively utilize the basic data of previous years, do detailed preliminary work, strengthen dynamic analysis, carry out gas well investigation, verify the pressure, production and liquid accumulation details of low-yield wells, and try to carry out the test and application of intelligent foam drainage technology. Through the remote-control system, the liquid accumulation diagnosis algorithm is developed to optimize and promote the transformation of foam drainage to intelligent mode, and the wellhead intelligent filling device is used to inject foam drainage agent into the tubing or tubing annulus of gas wells in real time, so as to reduce the amount of artificial foam drainage and achieve the purpose of drainage and gas production. This application of intelligent concepts can not only improve the drainage and stable production effect of gas wells, but also provides technical support for the construction of intelligent well stations. (2) Concerning the research of foam drainage and gas production technology, technicians can consider to establish and popularize the foam drainage technology system, classify the measures according to the different liquid accumulation conditions of various gas wells, comprehensively consider the drainage and gas production measures such as string optimization, negative pressure gas production and plunger drainage, and strengthen the application of composite drainage technology, which will definitely and effectively promote the work of foam drainage in gas fields. (3) In addition, the technical personnel shall comprehensively consider the formation pressure, production, liquid accumulation degree, well structure and so on, and classify and formulate the drainage gas production scheme and process technology according to the situation of each gas well, so as to ensure that the application of foam drainage gas production technology is more targeted. (4) In view of the sufficient solar energy on site in the gas field, the solar distributed intelligent injection and cluster defoaming equipment based on the Internet of Things and cloud services should be developed. Once the distributed intelligent injection and cluster defoaming mode is constructed, it will realize the green intelligent foam drainage and gas production through the mode of multi-well online collaboration. If intelligent filling equipment using solar energy can be developed successfully, it will be of great significance to the green transformation and low-carbon development of natural gas exploitation technology in China. It can reduce power consumption, which is equivalent to reducing carbon dioxide emissions, and will help the gas field achieve the carbon peaking and carbon neutrality goals in China.

In all, due to the high degree of external dependence of China in gas supply, it is thus suggested that operators of gas fields in China should pay much attention to the related innovation of this technology. In this way, the sustainable development of gas supply may be realized.

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Conflict of interest

The authors all declare that they have no conflict of interests regarding the publication of this paper.

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Biographies

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