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of the International Confrenence on Theory & Technology of Oil & Gas Production Engineering in 21st Century

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Symposium of the International Conference on Theory & Technology of Oil & Gas Production Engineering in 21st Century

By Xue Zhongtian *et al*.

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Preface

The papers that are included in this proceedings have been presented at the International Conference on Theory & Technology of Oil & Gas Production Engineering in 21^{st} Century (CTOPE'00): Advances in theory and technology of oil & gas production engineering, which was held at Xi'an Petroleum University (XAPU), Xi'an, China, on 12~14, April, 2000. The CTOPE'00 was organized by Xi'an Petroleum University, the Petroleum Society of Shaanxi Province, the Bureau of Changqing Petroleum Exploration, Petroleum University(Beijing), the Heriot-Watt University (England), and Edinburgh Petroleum Company.

The fascination of a growing industry of oil & gas in China is really inspiring. Especially in the beginning of 21^{st} century when Chinese government makes the plan to develop the western part of China, petroleum industry will play an important role in the national economy. Hence research programs in petroleum engineering are conducted and a lot of advances are achieved. These papers are some of the research results, including such aspects as distribution of remaining oil, enhanced oil recovery, waterflooding, fracturing & acidizing, formation pressure & stresses, petroleum chemical engineering, formation damage and reservoir protection, high energy gas fracturing, secondary oil recovery and tertiary oil recovery, reservoir numerical simulation and so on. Over 100 papers are presented in the conference and the symposium includes only part of them.

As the ever-progressing of petroleum industry and the China-western cooperation, all the paper writers and I hope to contribute to the cooperation by this symposium.

Acknowledgement and appreciation are due to all the contributors who submitted their proposals to CTOPE'00 for review. Needless to say, we could not have such high quality technical program without their contributions. I also wish to sincerely thank all the supporters and partners.

Xue Zhongtian

2000.4

CONTENTS

Study on Reasonable Well Pattern of High Pressure Waterflooding

Wang Jingrong[1] Xue Zhongtian[1]

Abstract The effect of waterflooding is affected by the injection pressure. When the injection pressure is too small , the effect of waterflooding is poor. When the pressure is too high, the formation is fractured easily around the wellbore. The reasonable pressure limit of waterflooding of a oilfield is calculated by calculating the in – situ stress changes cauesd by flooding. The development effects of inverted nine – spot pattern and five – spot pattern are compared, and the reasonable well pattern of the oilfield waterflooding is defined.
Keywords High Pressure, Waterflooding, Well Pattern, Development Plan

1 Introduction

Waterflooding is used in most of oilfields in the initial development as a secondary oil recovery method. The effect of waterflooding is affected not only by the well pattern of development , but also by the injection pressure. Generally, the higher is the injection pressure, the better is the effect. But the formation has a definite water injectivity, and when the water injected into the formation is beyond the water injectiviy, it can cause the formation pressure – out. When the pressure is beyond the formation fracture pressure, a micro – fracture is caused around the wellbore, and the effect of waterflooding is affected. The waterflooding pressure has a definite range.

According to the changes of in – situ stress, the reasonable pressure limits of high pressure waterflooding is defined. And on the reasonable injection pressure, a reasonable well pattern of a oilfield high pressure waterflooding is studied.

2 Determination of the High Pressure Waterflooding Reasonable Pressure Limits

2.1 In – situ Stress Changes Caused by High Pressure Waterflooding

Moralez, Abou – Sayed, Jones and Al – Saffar used a radial flow model (see Fig. 1) to determine the thermal stress. The thermal stress changes caused by high pressure water injection are calculated from

$$\sigma_\theta(r) = \begin{cases} \dfrac{-\beta E\Delta T[0.5 + r_w^2/(2r^2)]}{1 - v} & r_w < r < \Delta r_1 \\ \dfrac{\beta E\Delta T\Delta r_2}{2r^2(1 - v)} & r > \Delta r_1 \end{cases} \quad (1)$$

[1] *Petroleum Engineering Department XAPI, Xi' an, P. R. C.*

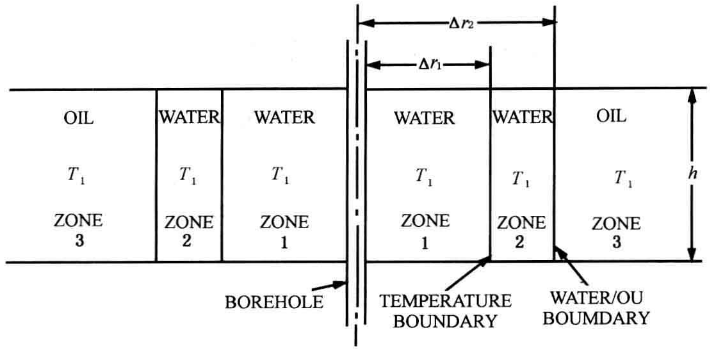

Fig. 1 Radial Flow Model

Where

$$\Delta r_1 = \left\{ \frac{V}{\pi h F_d \phi \left[\frac{\rho_f C_f + \rho_0 C_0 (1 - F_d)\phi}{\rho w F d \phi} + 1 \right]} \right\}^{0.5} \tag{2}$$

$$\Delta r_2 = \left(\frac{V}{\pi h F_d \phi} \right)^{0.5} \tag{3}$$

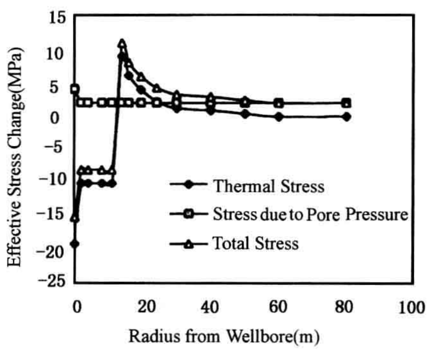

Fig. 2 Well S7 Stress Changes

There was only one water injection well, well S7, in a oilfield at the initial well pattern of development. The thermal stress changes of well S7 is ploted in Fig. 2. Note that the effect of the borehole stress becomes negligible within a few borehole radii. The thermal stress is relatively constant until Zone 2 is reached, then the abrupt temperature change gives rise to a reversal in the sign of the thermal stresses.

2.2 Stress Changes Resulting from Pore Pressure Build – up

As The volume of water injection increasing, the pore pressure must be boosting. It causes the in – situ stress changes. Haimson[2], Cleary[3], Perkins and Gonzalez[4] mentioned the expression of calculating the stress changes caused by pore pressure increasing.

$$\sigma_\theta(r) = \frac{K_p E}{1 - v} \left[\frac{1}{r^2} \int_{r_w}^{r} p(r) r \mathrm{d}r - p(r) \right] \tag{4}$$

The coefficient of pore pressure expansion, K_p, represents the difference between the bulk compressibility and matrix compressibility,

$$K_p = \frac{1 - 2v}{E} - \frac{C_{ma}}{3} \tag{5}$$

A similar method to thermal stress is applied here to calculate the in – situ stress changes caused by pore pressure. The in – situ stress changes due to pore pressure of well S7 is plotted in Fig. 2.

2.3 Total Stress Changes

The total change in effective stress is effected not only by the thermal stress change, but also by the pore pressure. The total stress change is gave by the sum of the thermal and pore pressure stresses. The total stress change of well S7 is plotted in Fig. 2.

2.4 Determination of Reasonable Pressure Limit

The undisturbed and modified in – situ stresses evaluated at the wellbore along with the bottomhole fluid pressures plotted with respect to the injection time are shown in a same figure. The bottomhole fluid pressure intersects the modified in – situ stress at a point. The pressure at the point is the pressure inducing a fracture.

This procedure is applied to calculate the reasonable pressure limit of well S7. The reseanable pressure of well S7 is 47.2MPa.

3 Design of Reasonable High Pressure Waterflooding Well Pattern

From the foregoing analysis, the reasonable pressure limit of waterflooding was defined on the in – situ stress changes due to water injection. In order to gain the performance after waterflooding, and extend the initial water injection experiment further, and provide the theoretical basis for developing fully, the waterflooding well pattern will be optimized on the defined reasonable injection pressure . The numerical simulation method is uesed to analyse the performance of the middle region of the oil – field production and injection wells which placed on inverted nine – point and five – point well patterns.

The perforated layer of the oilfield is the layer S_3. The porosity is 0.14, well depth is 3000m, initial reservoir pressure is 28.5MPa, reservoir net pay thickness is 10m, irreducible water saturation is 0.41, formation oil viscosity is 1.14mPa·s, surface oil density is 820kg/m^3, formation oil density is 650 kg/m^3.

The number of production and injection wells is 49 in the oilfield. These wells were placed on inverted nine – point and five – point well pattern. Many development models are calculated in this work. The typical models is as follow:

Model 1 is inverted nine – point well pattern. The bottomhole pressure of injection wells are 43.0MPa, and the bottomhole pressure of production wells are 19.0MPa. Model is Calculated for 300days as a year. It is predicted for 10 years.

Model 2 is five – point well pattern. The bottomhole pressure of injection wells are 43.0MPa, and the bottomhole pressure of production wells are 19.0MPa. The others are the same as model 1.

Model 3 is five – point well pattern. The bottomhole pressure of injection wells are 45.0MPa, and the bottomhole pressure of production wells are 19.0MPa. The others are the same as model 1.

In this paper, the pressure distribution, saturation distribution, rate of oil production, average formation pressure, water cut and injection – production ratio of the three typical models are predicted. The performances of the three models are plotted separately in Fig. 3~Fig. 5.

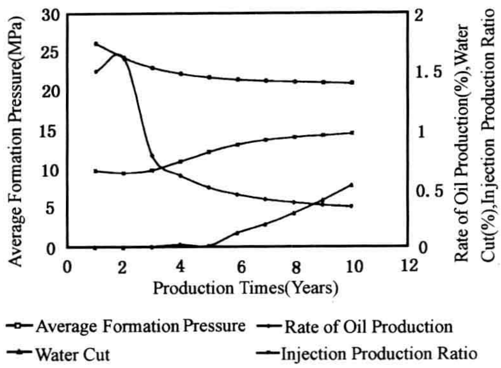

Fig. 3 Development Index of Model 1

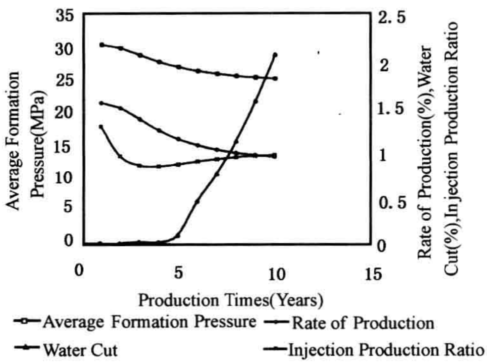

Fig. 4 Development Index of Model 2

The figures indicate that if the oilfield is developed on inrerted nine – point well pattern, the average formation pressure decreases rapidly. The pressure decreases 7.5MPa during 10 years, and the rate of production is smaller than 0.4%. This cannot be satisfied with the need of 2% rate of production. If the oilfield is developed on five – ponit well pattern, the average formation pressure decreases 3MPa during 10 years, and the rate of production can be 1% or so.

From the foregoing analysis and calculation, this oilfield is suit to be developed on five – point well pattern.

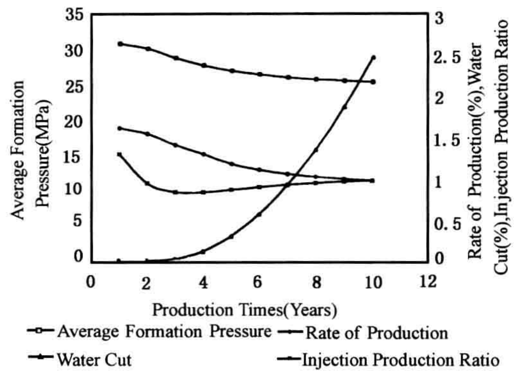

Fig. 5 Development Index of Model 3

4 Conclusions

The following conclusions can be drawn from the studies.

(1) The water injection (well bottomhole) pressure must be less than 47.2MPa in high pressure waterflooding. It can avoid fractures around the wellbore caused by the higher injection pressure, and affect the waterflooding effect.

(2) The inverted nine – point well pattern is not satisfied with the need of 2% rate of production when the oilfield is developed by flowing production method. It can be developed on five – point well pattern, and the bottomhole pressure of injection well is 45.0MPa, and the bottomhole pressure of production well is 19.0MPa.

Nomenclature

E—Young's modulus, MPa;
ρ_0—oil density, kg/m^3;
ν—Poisson's ratio, dimensionless;
β—coefficient in thermal expansion, 1/℃;
r—radius to arbitrary point, m;

F_d—oil displacement factor, fraction;
V—fluid volume injected, m^3;
ρ_f—rock density, kg/m^3;
ρ_w—water density, kg/m^3;
C_f—heat capacity of rock, J/(kg·K);
C_0—heat capacity of oil, J/(kg·K);
C_{ma}—matrix compressibility, 1/MPa.

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Successful Application of Carbon Dioxide Fracturing in Changqing Gasfield

Hu Wenrui[1] Lei Qun[1] Zhao Zhenfeng[1] Li Xianwen[1]

Abstract In 2000, Changqing Oilfield initiated the CO_2 fracturing study. The goal of the project was to improve natural gas recovery, and to compare production response of wells stimulated with CO_2 fracturing to those stimulated with conventional hydraulic fracturing. 13 wells were treated with CO_2 fracturing technique. The maximum proppant volume was $38m^3$. The ratio of proppant to liquid was about 27.3%. The concentration of liquid CO_2 was 41%~52% of the total injected volume. Fracturing treatments using 50% CO_2 and 50% gelled water in Changqing Gasfield have shown better production results than conventional treatments, especially in relative high permeability formations. By the comprehensive analysis and the comparison of well test information, the absolute open flow per well reached 70000 to 300000 m^3/d. The CO_2 fracturing technical system composed of treatment fluids, proppant, treatment techniques and equipments have been completed. The successful applications indicate that treatments using CO_2 fracturing technique will give us the bright prospect.

Keywords Carbon Dioxide Fracturing, Changqing Gasfield, Application, Gas Recovery

1 Introduction

Carbon dioxide has been used as a chemical agent to assist oil recovery since the early 1950's. Since 1960's CO_2 has been used widely as an additive to hydraulic fracturing and acid treatments. CO_2 has a density of 1.03 g/cm^3 and a critical temperature of 31℃. By the difference of CO_2 concentrations, pure CO_2 fracturing, CO_2 foam fracturing, and CO_2 energized fracturing techniques have been completed. The properties of the CO_2 fracturing technique can be described as follows:

1. The use of CO_2 reduces the amount of water injected and, consequently, the amount retained in the formations. The features of energized and flow back assistance are improved high velocity and efficiency of flow back, decreased formation damage, and improved production.

2. The fracturing liquids containing CO_2 distinguished with high viscosity and the property of good proppant transportation make higher injection rates and increased proppant concentrations easily. It is suited to deeper and large scale fracturing treatments.

3. During injection, water saturated with CO_2 forms carbonic acid. The low pH of approximately 3.5 is the best range for the protection of clay rich formations. Yet the pH is not so low that dissolution of iron containing minerals, and subsequent precipitation, becomes a problem.

4. There are other benefits of CO_2 which derive from its solubility. The interfacial tension of CO_2 saturated aqueous fluids is lowered to a level similar to that achieved with many surfactants.

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[1] *Petrochina Changqing Oilfield Company*, *P.R.C.*

The lowering of interfacial tension is important in reducing the capillary forces which can impede the production of treatment fluids imbibe by the pores in the formation.

CO_2 energized fracturing technique is used worldwide. There are two major differences between CO_2 fracturing treatments and conventional hydraulic fracturing treatments. The first is that liquid CO_2 is commingled with water or gel. The second is that the special equipment for CO_2 transportation, supplying and pumping must be prepared.

According to information statistics, the amount of CO_2 fracturing treatments in the world is about 17000 wells per year, and the percentage of foam fracturing treatments is about 25%. The ratio of CO_2 fracturing to the total foam fracturing treatments is 1/3, and the amount is about 1420 wells.

Because of the cost reason, N_2 used as energized gases in hydraulic fracturing is more than CO_2 used in other countries. CO_2 fracturing technique is most applicable in deep wells (1500～4000m). The volume of proppant used was in the range of 13 to 30 m^3. The maximum volume may be up to 50 m^3. The foam quality was about 20%～70%.

The application of CO_2 fracturing technique in China is just recent years. Jilin Oilfield first completed the application of the technique in oil formations with the depth of 1500m, the proppant volume of 8～15 m^3.

2 Fluid Properties

In conventional fracturing fluids, pH value is the key to maintain high viscosity of fluid. In order to obtain high cross link property of fracturing fluid, the gelled water fluid must hold in the condition of alkalescence but acidity which may result in the degradation of gelled fluid. For example, when pH value is about 7, the borate－crosslinked fracturing fluid has the viscosity greater than 100 mPa·s at the shear rate of $170s^{-1}$ and the shear time of 1 hour. If the pH value decreases to 6.5, the fluid viscosity consequently decrease to less than 50 mPa·s at the shear time of 10 min, and the viscosity is too low for proper treatment. The gallants used in CO_2 fracturing treatments are carboxymethyl or carboxymethyl hydroxypropyl guar gum in other countries. Because of the absence of such gallants in China, hydroxypropyl guar gum should be used, and the acidic crosslinker must be completed to meet the needs of CO_2 fracturing treatments.

2.1 Acidic Crosslinker

Based on the molecular structure of hydroxypropyl guar gum and acidic medium character, AC－8 acidic crosslinker has been synthesized, with which the crosslinking time is 20～30 s, the temperature tolerance is 110℃, the fluid viscosity 50～80 cP at 70～80℃ and shear time of 90 min. By test, the viscoelasticity of 0.5%HPG＋AC－8 mixed fluid shows the G' of 8.335Pa, and G'' of 2.952Pa, if the concentration of HPG increases to 0.7%, the mixed fluid has the G' of 11.99Pa, and the G'' of 6.835Pa.

2.2 Foaming Agent

Both foam stability and rheological property associate with foam quality. When foam quality range from 0 to 54%, gaseous phase disperse into liquid phase in the shape of gas bubble, and the bubbles disconnect with each other, the foam fluid shows Newtonian fluid property. When foam quality range from 54% to 74%, the bubbles expand, aggregate together, and interfere with each other, the viscosity and yield value increase slightly. In order to obtain high foam stability and long foam life, the selection test has been made. There are three foaming agent, FL-36, B-18 and YFP-1, used in the test, and the test results are summarized in Table 1.

Table 1 The Properties Contrast of Foaming Agents

Type	Foam Volume (mL)	Half-life (min)	Foam Quality (%)	Notes
FL-36	870	7.83	77.0	clear interface, fine bubbles, uniform distribution, clear water
B-18	820	6.08	75.6	unclear interface, nonuniform distribution milky white water
YFP-1	820	6.2	75.6	clear interface, fine bubbles, uniform distribution clear water
Abroad	860	7.5	76.7	clear interface, fine bubbles, uniform distribution clear water

2.3 Surface Tension Reducer

Fracturing fluids entered the reservoirs will connect with natural gas and result in two-phase flow. Because of the influence of capillary forces, the flow friction will increase, and it is difficult for fracturing to clean up. Changqing reservoir is a low permeability, low pressure, and gas bearing sandstone. If the formation pressure cann't overcome the friction of capillary forces, it is highly susceptible to low cleanup efficiency and formation damage by heavy water block. The cleanup additives selection test has been completed and the results can be given in Table 2. CQ-A1 and DL-10 are the choices in consequence of their tension reducing abilities, the interface tension will be less than 20mN/m with the concentration of 0.3%.

Table 2 The Results of Cleanup Additive Property Test

Type	0.2%		0.3%		0.5%	
	Surface Tension (mN/m)	Interface Tension (mN/m)	Surface Tension (mN/m)	Interface Tension (mN/m)	Surface Tension (mN/m)	Interface Tension (mN/m)
CQ-A1	21.91	1.83	18.71	3.32	17.54	3.95
DL-10	20.08	0.95	18.56	1.78	17.39	2.42
CF-5B	31.43	—	30.40	—	31.04	0.24
DL-8	23.78	0.88	23.10	0.66	23.05	0.02

Notes: DL-8 also has emulsion-breaking ability besides its cleanup property.

2.4 Comprehensive Performances of Fracturing Fluid

The ungelled guar gel has the pH value of 7.0, and the viscosity ranges from 120 to 130 cP. Gelled fluid has the pH value of 6.5, and the viscosity ranges from 310 to 420 cP. The rheological properties of the fracturing fluid are shown in Fig. 1 and Fig. 2.

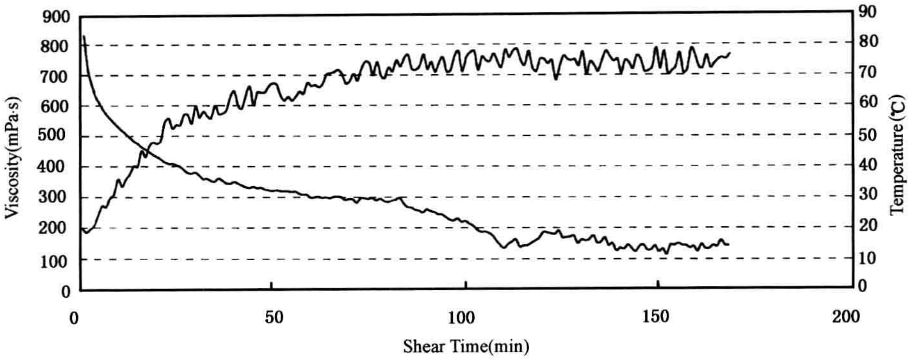

Fig. 1 Rheology of the Fluid

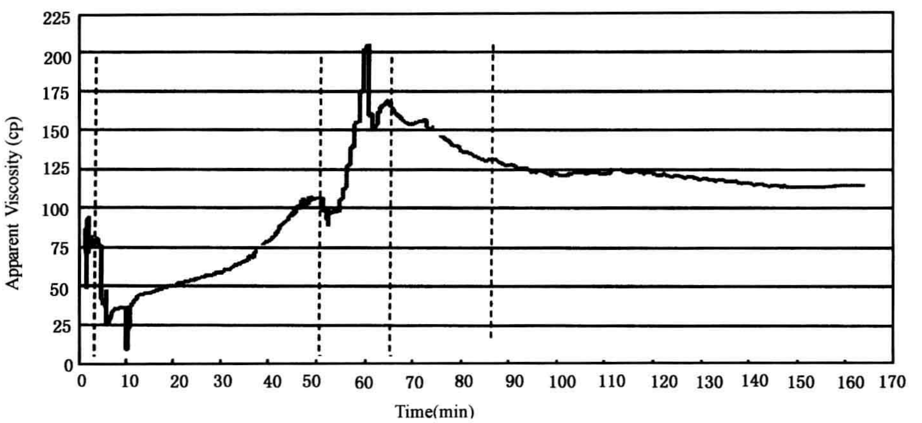

Fig. 2 Rheology of CO_2 Fracturing Fluid

The dynamic fluid loss coefficient obtained by test was about 0.000238～0.00032 m/min$^{1/2}$ in the conditions with the foam quality of 60%, the test temperature of 80℃, the test pressure of 7.0 MPa, and the shear rate of 170 s^{-1}. The permeability of core sample used in the test was 0.75 mD.

The fluid breaking behavior tests were performed at the temperature of 80 ℃. The results showed that the fluid viscosity breaked was 1.91 cP after 4 hours at static condition when ammonium persulfate used as breaker with the concentration of 0.01%, and the viscosity was 3.89 cP after 1 hour with the ammonium persulfate concentration of 0.06%.

3 Fracturing Design and Execution

3.1 Fracture Optimizing Design

The treatment designs were optimized with Pseudo 3D fracture design software, variables such as temperature filed of wellbore and formation, the temperature of treatment fluid, the pumping rate, treatment time, which will produce effect on CO_2 foam, has been considered in designing. Based on the design method of constant internal phase technique, the method of internal phase changed in adequate range has provided.

The constant internal phase technique means that the internal phase composed of proppant and CO_2 foam maintains uniform in the whole of pumping process by adjusting CO_2 injection volume.

The variant internal phase technique refers to that the injection volume of CO_2 changes in small range with increasing proppant concentration. The effectiveness of the technique in deep and relative high permeability formations has been proven. the design parameters of CO_2 fracturing treatments are summarized in Table 3.

Table 3 The Major Parameters of CO_2 Fracturing Designs

Items	Ratio of CO_2 to Gel	Foam Quality	Concentration of Gelling agent	Tubing (in)	Pumping Rate (m^3/min)	Proppant Volume (m^3)
Oil Well	1:1	52%～53%	0.55%～0.6%	2 7/8 in	2.5～3.5	20～28
Gas Well	50%～45%～35%～30%	52%～47%～42%～37%～32%	0.7%～0.75%	2 7/8 in or 3 1/2 in	2.0～3.0	20～38

3.2 CO_2 Commingling with Gelled Water

The surfactants must be added and a high－pressure three－way valve should be used to ensure that CO_2 is commingled with gelled water thoroughly. In the same time, foaming agent should be added in the fluid during fluid making up to obtain high foaming efficiency.

3.3 Techniques to Improve Proppant Concentration

Because the ratio of CO_2/slurry used in Changqing fracturing treatments is below 50% in general, the ways to obtain high proppant concentration are enhancement of fluid viscosity and maintenance of high pumping rate instead of using proppant concentrator.

3.4 Fluid Flowback Schedule

Based on the conclusion of Changqing fracturing treatment information analysis, the first step after treatments is to shutoff the well for 2 hours to make fracturing fluid break sufficiently. And then the fluid will be controlled to flush by flow bean. The purpose what we have done is to prevent proppant flowback or prevent fractures near wellbore closed.

3.5 Treatment Procedure

The surface set－up of CO_2 fracturing treatments used in Changqing Gasfield is illustrated in Fig. 3.