Exploration of Air Foam Oxygen Reduction Fracturing Technology

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Abstract. Air is a source of gas that is widely and easily obtained. Air fracturing is an ideal technology for reservoir stimulation in the future, and is also the best way to solve the pollution problem of oil and natural gas exploitation. The technology of air foam flooding and air drilling has achieved good results in oil fields at home and abroad. The feasibility of air foam fracturing technology is explored through studying the safety conditions for deflagration of air medium in gas reservoirs and the requirements of air foam fracturing technology. The results of preliminary laboratory study: at 100°C and 1MPa, the mixture of methane and air is safe when oxygen concentration is not higher than 11% in air, while the safety boundary is 5% for oxygen reduction requirement in air foam flooding. The viscoelastic properties of the developed air foam fracturing fluid can meet the requirements of conventional fracturing construction.

1. Introduction
In recent years, more than 90% of the new proven natural gas reserves in domestic oil fields are low permeability / ultra-low permeability tight reservoirs, with small pore throat and poor reservoir physical properties, air permeability is less than 0.1mD and porosity is less than 10%. Therefore, the nonlinear flow caused by the reservoir has a great influence on the development of the reservoir, it is difficult to establish an effective displacement pressure system in the reservoir, causing high injection-production pressure difference, low production rate and poor development efficiency. Fracturing technology is an important way to increase production in low permeability, ultra-low permeability and unconventional tight oil and gas reservoirs. Through massive volume fracturing, more matrix pores can be connected and the conditions of oil and gas seepage can be improved so as to achieve the effective development. However, the massive volume fracturing brings more questions, such as more fracturing fluid; endangering the ecological security and the surface water pollution. Nowadays, the society pays more attention on environment protection, and the cost of the liquid recovery / reuse technology is high, so the application of the reservoir reconstruction technology is faced with many problems. Air is a kind of material with low cost, wide source and easy access. Air fracturing is the best way to solve the pollution of reservoir reconstruction technology. It also provides the development imagination space for the technology of water-less / water-free reservoir stimulation.

2. The application of air foam flooding in oil field
As an effective way to reservoir stimulation with less water, gas foam enhanced oil recovery is widely used in major oil fields in China, such as foam drilling, foam fracturing, foam flooding, foam cement...
cementing, foam well washing. As the major oil fields in our country generally entered into the middle and late stages of development, the new development method is urgently needed to improve the recovery rate in tight, low porosity and low permeability reservoirs.

The biggest disadvantage of air in foam flooding is easy to corrode. Because of the different corrosion factors in the air foam flooding, the location and the state of corrosion are different. But as foam gas in foam flooding, air has the characteristics of wide material source, low cost and easy access. Air flooding has gradually become an effective means to improve oil recovery. Liu, Li Kang and so on had confirmed that the air injection is very suitable for low permeability reservoirs in the oilfield ZenPing well area and Xinjiang oilfield conducted field. The result of air foam flooding test in ZenPing well area: air and foaming agent can be separated into the dense core, the efficiency of oil displacement is increased by 32.9%, and the residual oil saturation is reduced to 21.1%. The low temperature oxidation reaction between the air and crude oil in the injected reservoir has a positive effect on reducing the oil viscosity and enhancing oil recovery.

3. The difficulty of air fracturing

The volume fracturing requires large amount of fracturing fluid. But many problems cannot be solved, for example, the large amount of compressed air in the fracturing, deoxidization speed can’t meet the requirements of explosion safety, the corrosion of air to the pipeline and so on. So the development of air fracturing technology is still in blank.

3.1. Explosion control

The content of O₂ in air is 21%, and it is easy to explode when it mix with oil and gas. Therefore, deoxidization is the biggest problem in the application of air fracturing technology. With the development of material science, the separation of O₂ in air has been very perfect. The final O₂ concentration in the treated air can be controlled at 2 ~ 10% [12]. However, whether the separation speed of O₂ in the air meets the discharge requirements of fracturing needs further research and testing.

According to the physical properties of each component in air, deep freezing, adsorption, membrane separation and other methods are used to separate oxygen and nitrogen from air.

(1) Freezing method: it is not suitable for continuous fracturing. At atmospheric pressure, the boiling point of oxygen is 90K/32℃, and the boiling point of nitrogen is 77K/25℃.

(2) Adsorption method: the process is simple and convenient, and low operating costs. In order to ensure continuous gas supply, more than two adsorption towers need to be used alternately. The separation speed is less than 66m³/min, and the purity of oxygen is about 93%.

(3) Membrane separation: the device is simple and convenient, less investment, but the oxygen concentration after treatment is between 28% and 35%.

3.2. Air fracturing equipment

Air compressor is the key technology of air fracturing equipment. Technology that is powered by compressed air has been used in the fields of vehicles, power plants, aviation and so on. With the improvement of national environmental emission requirements, pure electric powered air compressor has been rapidly developed [13].

From 1950 to 1990, air drilling was used in the United States to increase the speed of non-reservoir drilling, prevent leakage and so on. At the end of 80s, Xinjiang Bureau imported the first set of air drilling equipment in our country and started the field test of air drilling. After 2005, the air drilling technology developed rapidly, but because of the safety problems, it is still at the experimental and extending stage.

Figure 1 is the 8L-AT27GL/MH66 compressor unit of Kolb Company of the United States. It contains 5 stage air compression systems. The import pressure is 0.3-0.54MPa, and the outlet pressure is as high as 40MPa. The equipment has been carried out research experiment in the Tu ha oilfield in 2002 and 2003. And the compression medium is oilfield associated gas [14]. It is also necessary to study the high-efficiency air compressor matched with fracturing technology.
3.3. Corrosion problem

The oxygen content in the air is 21%, while the content of CO₂ in the air is very low, only 0.03%. Therefore, the corrosion in the gas injection well is mainly caused by the O₂ in the air. The O₂ in the air enters into the formation through the gas injection well. When it meets the formation water or the wet environment, the neutral or alkaline solution will be formed. As the concentration of the hydrogen ion is small, the potential of the hydrogen evolution reaction is negative, and the cathodic reaction of the metal corrosion process is usually the reduction reaction of oxygen in the solution of \(15-16\). At the same time, oxygen molecules as corrosion depolarizing agents aggravate the corrosion process and produce oxygen depolarization corrosion \(17\). The factors of oxygen corrosion in gas injection well include: O₂ concentration, temperature, salinity in formation water, pH value of formation water and so on \(18-19\).

It is also found that the displacement effect is getting better and better along with the increase of the O₂ content. Therefore, it is not feasible to reduce the oxygen corrosion by controlling the concentration of O₂ during the air flooding process.

There are two main methods to prevent the oxygen corrosion in the process of air flooding. One is the physical method, though internal anti-corrosion coating and low pressure air injection to avoid corrosion. The other is the chemical method, passive film. It makes the surface of steel become inert or not easy to start chemical reaction. At present, some oil fields in the United States took several measures to eliminate the possible of the corrosion and perforation of the tubing. The well with continuous tubing with gas injection were completed by using permanent injection packer to isolate the annular space and fill the preservative \(22\).

If the problem of pipe corrosion in the air injection process is solved, the application of air injection to EOR technology in the oilfield will be improved.

4. Feasibility of air foam fracturing

4.1. Study on deflagration conditions of air medium under fracturing conditions

Due to the limitations of the experimental conditions, the deflagration condition of the mixture of natural gas and air under the condition of 100℃ and 1MPa was studied in laboratory only.

In Table 1, when the oxygen concentration is reduced to 18%, with the increase of pressure, the upper limit of the explosion increases obviously. With the rise of the temperature, the upper limit of the explosion is slightly elevated, but the whole trend is stable. There is a good linear relationship between the pressure and the upper limit of explosion. The main factor affecting the upper limit of explosion is the initial pressure.

In Table 2, when the oxygen concentration is reduced to 11%, there is only a slight flashing phenomenon at the electrode when ignition occurs, as shown in Figure 2, and the upper and lower limits of the explosion are consistent.

According to the test, figure 3 shows the limit phase diagram of explosion at 100℃ and 1MPa. The safety critical oxygen concentration in methane-air premixed gas is over 11%, which satisfies the safety range of the highest oxygen content of 2-10% after air separation.
Table 1. Explosion limits of methane in air with an oxygen content of 18% at different temperatures and pressures

| Temperature/℃ | absolute pressure /MPa | Lower Explosive Limit (LEL) /% | Upper Explosive Limit (UEL) /% |
|---------------|------------------------|--------------------------------|--------------------------------|
| 60            | 1                      | 5.5                            | 16.75                          |
| 80            | 1                      | 5.5                            | 16.75                          |
|               | 0.6                    | 5.5                            | 15.25                          |
| 100           | 0.8                    | 5.5                            | 15.75                          |
|               | 1                      | 5.5                            | 17                             |
|               | 1.2                    | 5.5                            | 18.25                          |

Table 2. Explosion limits of methane in air with an oxygen content of 11% at different temperatures and pressures

| Temperature/℃ | absolute pressure /MPa | Lower Explosive Limit (LEL) /% | Upper Explosive Limit (UEL) /% |
|---------------|------------------------|--------------------------------|--------------------------------|
| 60            | 1                      | 6.5                            | 7.5                            |
| 80            | 1                      | 6                               | 7.75                           |
| 100           | 0.6                    | 5.75                           | 7.5                            |
|               | 1                      | 6                               | 8                              |

Figure 2. Critical limit diagram of explosion
Figure 3. Explosion limit phase diagram at 1MPa, 100℃

4.2. Effect of air foam flooding
Since 1967, Amoco, Gulf and Chevro companies carried out field experiments in the United States with air injection in light oil reservoirs. Air foam injection had been carried out in Yumen Oil field in 1964. Since the end of 70s, air foam injection has been carried out in Shengli, Daqing and Baise oil fields. Since twenty-first Century, air flooding technology has developed in low permeability reservoirs and extra high water cut reservoirs in Changqing, Yanchang, Zhongyuan oil field [23]. It can be seen from table 3 that the effect of air foam flooding is better than other gases. Therefore, air foam fracturing has a good space for development.
Table 3. Effect of injected gas foam on oil displacement efficiency in laboratory

| Influence factor | Analog parameters     | Increase of recovery rate /% | Decrease of water content /% |
|------------------|-----------------------|------------------------------|------------------------------|
| development model| water injection       | 3.4                          | -2.1                         |
|                  | N₂ injection          | 23.8                         | 6.5                          |
|                  | air injection         | 27.2                         | 13.7                         |
|                  | N₂ foam injection     | 28                           | 9.3                          |
|                  | air foam injection    | 46.4                         | 20                           |

4.3. Exploration of air foam fracturing fluid

The air foam foaming agent developed in this paper can produce accumulating air foam with uniform membrane structure under high pressure. In Figure 4, the accumulating air foam comes from air bubble group, which is formed by the aggregation of "bubble of mono body fluid". They are independent and adhere to each other. In Figure 5-6, GX-22 air foam fracturing fluid system has good foaming ability and viscoelastic properties, the temperature resistant capacity reaches 110℃. The better air foam quality can meet the requirement of sand carrying and reduce the water consumption.

![Figure 4. the generation of an accumulating air foam (25 C, 15MPa)](image)

![Figure 5. Elastic modulus of GX-22 air foam system](image)

![Figure 6. The resistance to temperature and resistance of GX-22 air foam system](image)

5. Conclusion

Air fracturing is a feasible direction, but more detailed safety and basic theoretical research are needed. By studying the safety limit of explosion, the effect of the chemical reaction between air and crude oil, the influence of the compressed air on the law of seepage and the relationship between the air foam size and the microstructure shape after the air oxygen reduction fracturing fluid enters the reservoir pore, the field experiment of air foam fracturing with oxygen reduction can be carried out in the future. By exploring the influence of air on equipment and construction conditions, creates conditions for the application of air oxygen reduction fracturing technology.
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