Initiation characteristics of tight sandstone reservoir under different fracturing fluid infiltrations

Yin Zhang1*, Rangang Yu1, Wendong Yang1, Yong Tian2, Zhicheng Shi1, Chengxiang Sheng1 and Hongyuan Sun1

1College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao 266580, China
2School of Science, Qingdao University of Technology, Qingdao 266520, China
*Corresponding author’s e-mail: b18060008@s.upc.edu.cn

Abstract: True triaxial hydraulic fracturing experiments were carried out on artificial analogue rock samples (AARS) of tight sandstone to analyze initiation characteristics under different fracturing fluid (FF) infiltrations. Moreover, the initiation was monitored by acoustic emission (AE) system. The results show that: FF fracturing has the lowest initiation pressure (37.7 MPa) and average pressurization rate (0.2 MPa/s), and takes the longest time for initiation (209 s). Besides, AE signal is scattered and no extension appears after initiation. FF + temporary plugging agent (TP) fracturing has the highest initiation pressure (43.5 MPa) which is lower than extension pressure, and it also has higher pressurization rate and amplitude peak as well as shorter time for initiation compared with FF fracturing. As for FF + sleeve fracturing and FF + nano-organoboron crosslinking agent (NBC) fracturing, they have much shorter time for initiation as well as higher evidently average pressurization rate and amplitude peak. Extension pressure is lower than initiation and almost all AE signal is concentrated at initiation moment.

1. Introduction

Initiation is affected by many factors such as crustal stress, reservoir properties, FF infiltration and injection pressure [1]. Because crustal stress and reservoir properties cannot be changed easily, changing FF infiltration has been popularized so as to achieve more suitable initiation characteristics.

Innumerable studies have been conducted on the effect of FF infiltration on initiation characteristics of tight sandstone reservoir. Many models show that FF viscosity has a significant effect on infiltration, and the viscosity can be increased with NBC adding, increasing initiation pressure and saving time for initiation [2-3]. TP fracturing gains its popularity, preventing FF from infiltrating into reservoir [4-5]. Sleeves and perforations can concentrate fluid pressure to achieve better initiation effect and 60° is regarded as the best perforation phase [6]. However, since the diversity and complexity of reservoir properties, consistent conclusions have not been found [7]. Up to now, there have been few comparative studies on initiation effect of FF, sleeves, NBC and TP.

Therefore, this work carried out hydraulic fracturing experiments on AARS of 1832.5 m deep tight sandstone reservoir in Shengli Oilfield, China. In order to reflect different infiltrations, four fracturing methods were applied: FF fracturing, FF + sleeve fracturing, FF + NBC fracturing and FF + TP fracturing. For typical data, the effect of fracturing method (FF infiltration) on initiation characteristics of tight sandstone reservoir was fully comparative studied, providing references for field fracturing.
2. Experimental setup

Crustal stress ($\sigma_h$, $\sigma_H$, $\sigma_v$) of reservoir was 31.3MPa, 44.1MPa, and 33.1MPa, respectively. And AARS were made according to reservoir parameters. Furthermore, hydraulic fracturing experiments were carried out under different fracturing methods (FF infiltrations).

2.1. Rock sample

Taking the difficulty of natural rock samples collection into consideration, natural cores with the diameter of 2.5cm were drilled in the target reservoir (Fig. 1), and reservoir parameters including tensile strength (TS), compressive strength (CS), Young’s modulus ($E$), Poisson’s ratio ($\mu$), density ($\rho$), porosity ($n$) and permeability ($k$) were measured. Based on the parameters, AARS were made according to components’ proportions (Table 1) with 42.5 composite Portland cement, medium sand and 10% polycarboxylate superplasticizer (PCE). And AARS were effective since the parameters error was less than 10% (Table 2) [8]. Fig. 2 shows two types of cubic AARS with edge length ($L$) of 10.0cm, and vertical holes with diameter ($D$) of 1.0cm and depth ($H$) of 8.0cm were drilled on surface center of AARS. Besides, screw perforations with phase angle ($\phi$) of 60°, diameter ($d$) of 0.2cm and length ($l$) of 0.5cm were also drilled in the middle of AARS (4.0–6.0cm). In addition, sleeves that matched holes were added in type II.

![Figure 1. Natural cores of tight sandstone reservoir in Shengli Oilfied, China.](image1)

Table 1. Components’ proportions of AARS.

| Cement: sand | Water: cement | PCE: cement (%) |
|--------------|---------------|----------------|
| 1:1.2        | 0.4           | 2              |

![Table 2. Parameters of tight sandstone reservoir and AARS.](image2)

|                    | $E$ (GPa) | $\mu$ | TS (MPa) | CS (MPa) | $\rho$ (g/cm$^3$) | $n$ | $k$ (mD) |
|--------------------|-----------|-------|----------|----------|-------------------|-----|---------|
| Tight sandstone reservoir | 13.76     | 0.274 | 6.21     | 50.82    | 2.35              | 0.07| 0.24    |
| AARS               | 12.81     | 0.295 | 5.80     | 49.33    | 2.31              | 0.07| 0.26    |

![Figure 2. Two types of AARS.](image3)

2.2. Experimental equipment

A true triaxial hydraulic fracturing experiment system composed of pressure chamber, pressure source, constant-flux pump, intermediate container, monitors and other auxiliary devices was developed (Fig. 3). And SAEU3H AE system helped to monitor initiation of AARS. AARS were placed in pressure chamber, and FF (TP, NBC) were filled in intermediate container. There were pressure sensors in pressure source and constant-flux pump to monitor confining pressure and injection pressure. Any air between interfaces of AE sensors and AARS was removed by high-temperature vacuum insulating silicone grease to make mismatch of acoustic impedances be minimized. And noise was shield by setting threshold as 35dB [9].
2.3. Experimental conditions

The confining pressure applied to AARS was equal to crustal stress of reservoir. TP was a kind of organic oil-soluble material with the concentration of 0.8%. FF was 0.2% hydroxypropyl guar gum solution with the viscosity ($\eta$) of 112mPa·s, and $\eta$ can reach 425mPa·s with 0.4% NBC adding. Injection delivery ($q$) was constant at 0.3mL/s. In addition, type I AARS were used in Exp. No. 1, No. 3 and No. 4; type II were used in Exp. No. 2.

3. Experimental results and analysis

Each experiment was repeated ten times to minimize the experimental data dispersion, and the typical data closest to average initiation pressure ($p_i$) and time for initiation ($t_2$) were used for further analysis (Table 3, Fig. 4). Table 4 shows experimental results including $p_i$, $t_2$, average pressurization rate ($p_r$) and amplitude peak ($A_p$) of typical data.

| Exp. No. | Fracturing methods     | $p_i$ (MPa) | $t_2$ (s) | Average |
|----------|------------------------|-------------|-----------|---------|
| 1        | FF fracturing          | 39.4        | 37.7      | 38.1    |
|          |                        | 32.1        | 35.1      | 33.1    |
|          |                        | 39.2        | 39.6      | 39.2    |
|          |                        | 40.5        | 44.9      | 40.5    |
|          |                        | 40.9        | 48.7      | 40.9    |
|          |                        | 43.6        | 33.6      | 43.6    |
|          |                        | 39.5        | 31.1      | 39.5    |
|          |                        | 35.1        | 39.9      | 35.1    |
|          |                        | 40.9        | 42.1      | 40.9    |
|          |                        | 43.6        | 35.7      | 43.6    |
|          |                        | 49.1        | 53.7      | 49.1    |
| 2        | FF + sleeve fracturing | 33.5        | 39.2      | 33.5    |
|          |                        | 41.7        | 44.9      | 41.7    |
|          |                        | 42.1        | 48.7      | 42.1    |
|          |                        | 39.6        | 33.6      | 39.6    |
|          |                        | 43.6        | 31.1      | 43.6    |
|          |                        | 49.1        | 39.9      | 49.1    |
|          |                        | 53.7        | 42.1      | 53.7    |
|          |                        | 56.5        | 39.4      | 56.5    |
| 3        | FF + NBC fracturing    | 44.1        | 42.9      | 44.1    |
|          |                        | 42.9        | 35.2      | 42.9    |
|          |                        | 45.2        | 29.4      | 45.2    |
|          |                        | 39.8        | 39.2      | 39.8    |
|          |                        | 43.5        | 53.7      | 43.5    |
|          |                        | 47.8        | 41.7      | 47.8    |
|          |                        | 51.4        | 43.5      | 51.4    |
|          |                        | 39.1        | 41.7      | 39.1    |
|          |                        | 43.5        | 47.8      | 43.5    |
|          |                        | 51.4        | 43.5      | 51.4    |
| 4        | FF + TP fracturing     | 45.8        | 45.9      | 45.8    |
|          |                        | 43.5        | 45.9      | 43.5    |
|          |                        | 37.2        | 47.8      | 37.2    |
|          |                        | 39.1        | 47.8      | 39.1    |
|          |                        | 41.7        | 47.8      | 41.7    |
|          |                        | 43.5        | 47.8      | 43.5    |

Bold indicates the typical data close to the average.
Table 4. Experimental results of typical data.

| Exp. No. | Fracturing method     | $p_i$ (MPa) | $t_1$ (s) | $p_r$ (MPa/s) | $A_p$ (dB) |
|----------|-----------------------|-------------|------------|--------------|------------|
| 1        | FF fracturing         | 37.7        | 209        | 0.20         | 63.5       |
| 2        | FF + Sleeve fracturing| 39.2        | 56         | 1.12         | 76.6       |
| 3        | FF + NBC fracturing   | 39.8        | 51         | 1.33         | 74.7       |
| 4        | FF + TP fracturing    | 43.5        | 93         | 0.60         | 63.7       |

Fig. 5 shows the typical injection pressure – experiment time ($t$) curves. Obviously, injection pressure does not increase significantly from 0 to $t_1$ ($t_1$ indicates time required for FF to fill the holes of AARS). In this process, FF is not squeezed and cannot infiltrate rock matrix [10]. Because hole volume (6.3cm$^3$) and $q$ of each experiment are the same, $t_1$ (about 21s) is almost invariant. After $t_1$, injection pressure grows significantly and generates hydraulic fractures when it reaches $p_i$ at $t_2$. After $t_2$, injection pressure – $t$ curves present different patterns.

3.1. Initiation pressure

Generally, initiation pressure ($p_i$) is greater than the sum ($37.1$MPa) of $\sigma_h$ ($31.3$MPa) and TS ($5.8$MPa). And due to weaker infiltration inhibited by sleeves, NBC and TP, $p_i$ of Exp. No. 2–4 is increased compared with that of Exp. No. 1. Moreover, dense artificial barrier formed by TP, preventing fluid pressure from transmitting to rock sample matrix, leads to the highest $p_i$ (Exp. No. 4, 43.5MPa) [11]. At initiation moment, injection pressure of Exp. No. 1–3 decreases rapidly and that of No. 4 drops slightly. After initiation, continuous extension appears in Exp. No. 2–4 and injection pressure fluctuates frequently. Thereinto, peak values of each fluctuation (extension pressure) of Exp. No. 2 and No. 3 are lower than $p_i$, and those of Exp. No. 4 are higher than $p_i$ because of the plugging effect of artificial barrier.
3.2. Time for initiation
Under the constant \( q \), inhibited infiltration can not only increase \( p_i \) but also save time for initiation (\( t_2 \)). Compared with \( t_2 \) of Exp. No. 1, that of No. 2 and No. 3 decreases by 73.2% (56s) and 75.6% (51s), respectively. Besides, Exp. No. 4 takes longer \( t_2 \) (93s) because FF infiltration and artificial barrier formation begin simultaneously, and plugging effect of artificial barrier can be fully reflected when it is completely formed.

3.3. Average pressurization rate
Pressurization rate indicates injection pressure variation per unit \( t \) from \( t_1 \) to \( t_2 \). The average pressurization rate (\( p_r \)) is the secant slope of injection pressure – \( t \) curves from \( t_1 \) to \( t_2 \), and is calculated as \( p_r/(t_2-t_1) \) if the exceedingly low injection pressure before \( t_1 \) is ignored. Obviously, \( p_r \) of Exp. No. 2 and No. 3 is much higher than that of No. 1 because sleeve and NBC increase \( p_i \) and decrease \( t_2 \) greatly. Although \( p_i \) is significantly increased by TP (Exp. No. 4), the reduction of \( t_2 \) is relatively slight and therefore, \( p_r \) is only 0.6MPa/s. In addition, the lowest \( p_i \) (37.7MPa) and the longest \( t_2 \) lead to the lowest \( p_r \) (0.2MPa/s) since the infiltration is not inhibited (Exp. No. 1).

3.4. AE amplitude
When AARS matrix is disturbed by FF, even if there is no visible fracture, AE signal will still be generated [12]. Fig. 6 shows typical injection pressure – \( t \) curves and amplitudes. Since the noise has been shielded, there are three sources of AE signal: the first is caused by confining pressure, the second is generated by injection pressure, and the third is attributed to FF infiltration. Generally, AE signal is widely distributed in the whole fracturing process. However, because of inhibited infiltration (Exp. No. 2~4), innumerable AE signal generated by FF infiltration is reduced [13].

AE signal is detected at about \( t_1 \). Due to the strongest infiltration of Exp. No. 1, AE signal appears in the whole fracturing process. Before initiation, because Exp. No. 1 and No. 4 have stronger infiltration than Exp. No. 2 and No. 3 do, more AE signal is generated, releasing more energy and decreasing amplitude peak (\( A_p \)) at initiation moment (63.5dB, No. 1; 63.7dB, No. 4). At initiation moment, with the help of sleeve and NBC, more AE signal is concentrated, increasing \( A_p \) (76.6dB, No. 2; 74.7dB, No. 3). After initiation, frequent fluctuation of injection pressure indicates that fractures extend continuously, and AE signal is generated accordingly. The distribution of AE signal matches well with injection pressure fluctuation.
4. Conclusions
Relatively higher initiation pressure (43.5MPa) can be caused by fracturing fluid (FF) + temporary plugging agent (TP) fracturing, and extension pressure is higher than initiation pressure with TP accumulation. In addition, FF fracturing, FF + nano-organo boron crosslinking (NBC) fracturing and FF + sleeve fracturing have relatively lower initiation pressure and injection pressure decreases sharply at initiation moment, resulting in extension pressure is lower than initiation pressure.

FF + sleeve fracturing and FF + NBC fracturing take shorter time for initiation (56s and 51s, respectively), and FF + TP fracturing and FF fracturing take longer (93s, 209s).

FF fracturing has the lowest average pressurization rate (0.2MPa/s). Average pressurization rate can be increased significantly by sleeve and NBC.

Sleeve and NBC have an ability to concentrate acoustic emission (AE) signal at initiation moment and increase amplitude peak apparently.

AE signal can be concentrated at initiation moment and amplitude peak is apparently increased by sleeve and NBC. And scattered AE signal is caused by FF and TP.

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