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Experimental Evaluation of the Integrated Composite Perforation System under Simulated Tight Reservoir Conditions

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Abstract. This paper aims to evaluate the performance of the integrated composite perforation system in tight reservoirs. To simulate complex pressure conditions of the reservoir, a perforation test device was developed in accordance with API RP 19B sections 4.2 and 4.4 procedures, and a set of test evaluation methods was designed. Using a type 4-1/2in perforating charge and pre-propellant charge, a tight sandstone target with rock physical characteristics similar to the real reservoir were selected for the perforation test under simulated reservoir pressure, pore pressure, and wellbore pressure. The characterization of the perforation tunnel and fracture morphology using CT scanning and thin-section analysis techniques. The results show that under the simulated reservoir pressure conditions, the integrated composite perforation system reduces the penetration depth by nearly 8% compared with the conventional perforation, improves the average flow efficiency by 17.2%, and creates multiple 40mm-100mm extended fractures at the end of the tunnel, the perforation and fracture enhancement is improved by an average of 1.34 times.

1 Introduction

Future development is now centered on deep tight low-permeability oil and gas reservoirs. Owing to deep burial, tight lithology, and poor physical properties of the reservoir, when conventional perforating charges are used for perforating completion, the high impact of the jet destroys the flow tunnel formed by the perforation between the reservoir and the wellbore, forming a compacted zone of approximately 6mm to 13 mm, which negatively affects the productivity of the well and subsequent reservoir implementation [1-2]. To reach the desired productivity, it is crucial to have clean perforating channels, and various enhancement techniques, such as StimGun and self-cleaning are also proposed.

The integrated composite perforating system refers to a pre-propellant charges loading in the front of a conventional shaped charge, which is formed in series in the perforating gun (as shown in Figure 1). By exploiting the mechanism of velocity difference between explosive and propellant combustion, secondary energy release is achieved by transporting the fragmented propellant into the perforation tunnels by the vortex field gravity generated by the high-velocity jet stream during energy accumulation perforation, which generates a large amount of gas to clean the compacted zone and expand to form fractures [3-4]. This technology was proposed in the 1980s, and by the mid-1990s, it began to be applied in various oilfields [5-10]. For the evaluation of conventional perforation efficiency, various manufacturers often use the method recommended by API RP 19B to test the fluidity of the target before and after perforation [11], and then cut the target to physically measure the morphology of the perforation tunnel and analyse the damage of the perforation tunnel using scanning electron microscopy [12] to evaluate perforation efficiency. In 2023, Xu Xinhua[13] et al. established a aftereffect perforation productivity evaluation model, based on the principle of equivalent flow rate in the composite reservoir and proposed that perforation depth and radial permeability are the main controlling factors for perforation efficiency. However, the current evaluation of perforation efficiency in tight reservoirs is mainly based on the feedback of actual field production capacity, and there is a lack of effective laboratory evaluation methods.

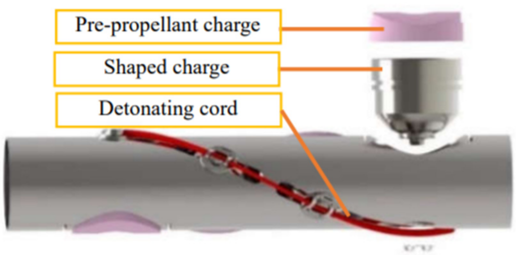

FIG.1. Integrated composite perforating system

This article combines the conditions of tight oil and gas reservoirs, develops a perforation performance testing device under simulated reservoir pressure conditions and conducts the integrated composite perforation tests. By combining CT scanning and thin-section analysis technology, the perforation tunnels are characterized to achieve comprehensive efficiency evaluation of the integrated composite perforation system.

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2 Test equipment setup and test evaluation method

During well completion, the test results of the surface API concrete target are significantly different from the perforation depth under near-well conditions of the reservoir. Therefore, the models created under traditional conditions are no longer suitable for predicting perforation penetration, perforation channel shape and flow efficiency under downhole conditions.

In order to acquaintance the perforation performance of the integrated composite perforating system under the actual reservoir conditions, it is necessary to carry out the experimental research on the integrated composite perforating system, which will be helpful for guiding the design of composite perforating completion and correctly evaluating the actual reserves of oil and gas wells, and at the same time, guiding the development and optimization design of the products.

2.1 Test equipment

The actual reservoir is mainly affected by the pressure of the overlying strata (axial stress ∂_z) and the extrusion pressure of the surrounding rock in the horizontal direction (horizontal stress ∂_x, ∂_y) under the formation conditions. At the same time, due to external forces, the rock skeleton particles and the fluid saturated in the pores during the formation process jointly exert external support, known as rock skeleton stress and pore pressure. In order to simulate the stress conditions of rocks in actual oil reservoirs, a test apparatus for simulating reservoir pressure conditions for perforation was designed based on the API-RP 19B 2021 “Evaluation of Well Perforators” 4.2 and 4.4 released by the American Petroleum Institute’s, as shown in Figure 2. This equipment can simulate and test the performance of various perforation systems and the influence of various factors on well productivity, and through analysis and compilation, it can evaluate perforation efficiency. The results are used to optimize the perforation plan based on the results to improve the reservoir recovery rate.

The interior of the device is divided into three separate compartments, which are used to establish reservoir pressure, pore pressure, and wellbore pressure. The rock core, covered with a rubber sleeve, is placed in the overburden pressure compartment to simulate the reservoir’s stress on the rock by applying pressure to the target sleeve. At the same time, the target sleeve is subjected to the overburden pressure, isolating the pore pressure chamber from the reservoir pressure compartment.

The core pore pressure was simulated by pressurizing the bottom end of the core to allow fluid to enter the core pores until they were interconnected. The perforating gun unit was placed in the pressure space of the wellbore, and the firing direction of the shaped charge was parallel to the axis of the sandstone target.

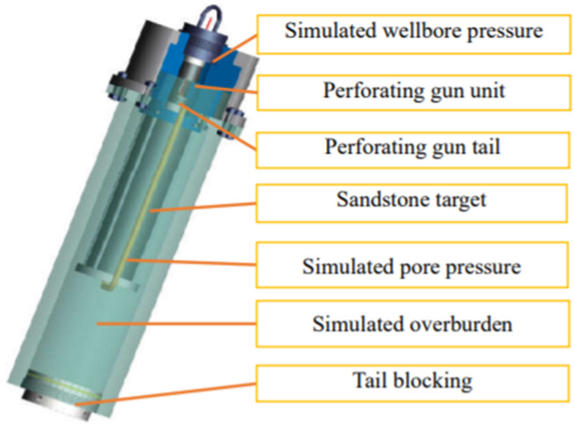

FIG. 2. Structure diagram of the simulated three-chamber pressure test equipment

2.2 Manufacturing of test targets

In order to simulate the actual characteristics of the reservoir rock, this experiment according to the target reservoir Lufeng 14-8 Wenchang Formation reservoir characteristics (Table 1), Type of reservoir: compact, low ~ medium porosity, extremely low ~ medium permeability reservoir. Through field investigation of rock outcrops and physical property parameter testing, Sichuan red and gray sandstones, as well as Shandong purple sandstone, were ultimately selected. All three sandstone targets have a length of 25 mm and a cross-sectional area of 5 cm^2. (Experimental target parameters in Table 2). They were carved according to the size of Berea sandstone target (diameter 7in, height 30in) specified by API (as shown in Figure 3.).

FIG. 3. Sampling diagram of sandstone target

Table 1. Reservoir parameters of Wenchang Formation in Lufeng 14-8

Reservoir depth /m	UCS /MPa	Porosity / %	Permeability / (10^{-3} μm^2)
3600 ~ 4000	31-137	3.5 ~ 19	0.1 ~ 271.4

Table 2. Physical properties of sandstone target rocks

Rock types	Average UCS /MPa	Density /g/cm^3	Porosity / %	Permeability / $10^{-3}\mu m^2$
Red sandstone	48.32	2.41 ~ 2.44	7.91	0.19
Gray sandstone	74.51	2.51 ~ 2.54	9.10	0.20
Purple sandstone	105.0	2.46 ~ 2.51	5.56	0.14

2.3 Test evaluation method

In order to make the sandstone target more representative of subsurface conditions, according to Section-IV of API 19B "Evaluation of Well Perforators," the sandstone target was placed in a ventilated constant temperature oven for 100°C/24h drying operation.

After drying, the test target was placed in a container connected to a vacuum pump to further remove water and dissolved gases in the pores. The evacuation time was at least 6 hours. It is then poured into a solution containing 3% sodium chloride (NaCl) and saturated under pressure. Pressurized to (18~20) MPa, and repeatedly pressurized until the pressure remains stable. The porosity of the core was calculated using the weighing method.

Place the saturated sandstone target into the rubber sleeve and load it into the testing apparatus that simulates reservoir conditions. The reservoir pressure, pore pressure, and wellbore pressure were increased to the predetermined values to detonate the shaped charge. Then the wellbore pressure and pore pressure equalized, and the reservoir pressure and pore pressure were slowly released at the same rate. When the wellbore and pore pressures reach atmospheric pressure, open the testing apparatus and remove the sandstone target. The shot core sample is split to visualize the perforation tunnel by CT scanning and injecting thin sections, evaluating the degree of impact of perforation on the rock. Finally, samples of the tested sandstone were collected to test the uniaxial compressive strength of the rock to facilitate data analysis.

3 The test of the composite perforation system

3.1 Perforation test under simulated reservoir conditions

3.1.1 Test Conditions and Scheme

Based on the reservoir pressure of Wenchang Formation in Lufeng 14-8, and according to formation stress and completion fluid density, the pressure conditions of reservoir pressure of 60MPa, pore pressure of 30MPa and wellbore pressure of 25MPa were determined. The integrated composite perforating system is formed by using the 4-1/2in shaped charges and pre-propellant charges. Perforating tests were carried out on three sandstone targets according to the experimental procedure, as shown in Table 3.

Table 3. Test scenario of perforation

Rock type	Perforating type
Red Sandstone	4-1/2 in shaped charge
	4-1/2 in shaped charge+ pre-propellant charge
purple Sandstone	4-1/2 in shaped charge
	4-1/2in shaped charge + pre-propellant charge
Gray Sandstone	4-1/2 in shaped charge
	4-1/2in shaped charge + pre-propellant charge

3.1.2 Test result Analysis

3.1.2.1 Comparative Analysis of Penetration Performance

After simulating the reservoir perforation test, we analysed the perforation depth, diameter and pore volume. The perforation tunnel was filled with water injected from the hole entrance at the end of the test target. We recorded injected water volume as the pore volume. Specific test data can be found in Table 4 and Figure 7. All of them have standoff of 28mm, and all of them have a gap of 25mm.

Table 4. Analysis and statistics of perforation test data

Rocks type	UCS /MPa	Perforating type	DOP /mm	EH /mm	Pore volume /mm^3
Red sandstone	48	-	370	8.7	7753.2
	51	pre-propellant	340	9.65	9360.8
Improved performance (%)	-	-	8.1	13.2	20.7
Purple Rock	63	-	310	8.8	7028.9
	65	pre-propellant	280	9.4	8210.7
Improved performance (%)	-	-	9.7	6.8	16.8
Gray Sandstone	75	-	320	9.4	8431.8
	72	pre-propellant	300	10	9964.8
Improved performance (%)	-	-	6.3	6.4	18.2

It can be known through data analysis. The uniaxial compressive strength of rock has a significant influence on perforation performance. Under the same conditions, the perforation penetration decreases as the compressive strength of the rock increases, which is consistent with the observed test results. Through analysis of the test data, several findings emerge. Firstly, under simulated reservoir pressure conditions, the integrated composite perforation system reduces the average perforation depth by 8.0%, increases the average perforation diameter by 8.8%, and increases the average perforation volume by 18.6%. This suggests that the integrated composite perforation system interferes with the metal jet, influencing the perforation depth, but contributes to pore expansion and volume enlargement. This is consistent with the theory proposed by Lu Kun[14] et al. that the larger the perforation aperture, the more favourable the crack propagation. Notably, the expanding hole effect of the pre-perforation composite system is most prominent in red sandstone due to its relatively low uniaxial compressive strength. However, the effect weakens as the compressive strength of the rock increases.

3.1.2.2 Analysis of Perforation Efficiency

To analyse the stimulation effect of the integrated composite perforating system, a comparison was made on the flow efficiency of three groups of sandstone targets after conducting a simulated reservoir perforation test. The test results are presented in Table 6. Under identical conditions of temperature, pressure, and fluid viscosity, the average flow efficiency of the integrated composite perforating system demonstrated a remarkable 17.2%

improvement over conventional perforation. As show in table 5.

Table 5. Test data of flow efficiency

Rock type	type	Flow rate /cm^3/s	Performance improvement/%
Red Sandstone	Conventional	0.61	18.0
	Integrated	0.72	
Purple Sandstone	Conventional	0.51	13.7
	Integrated	0.58	
Gray sandstone	Conventional	0.65	20.0
	Integrated	0.78	

To analyze the stimulation mechanism of the integrated composite perforating system in more detail, we characterized the morphology of the perforations and the microscopic physical properties of the rocks using CT scanning and analysis of large-sized thin section. We conducted a comprehensive comparative analysis to evaluate the effects of conventional perforation and the integrated composite perforating system on tunnel formation.

The CT scan of the rock core (see Figure 4) provides image processing results, with gray indicating the core, white representing the metal slug, and red denoting cracks. The CT scan structure offers clear visibility of the perforation tunnels from the end face to the bottom. When conventional shaped charges are used to perforate sandstone targets, metal particles deposited along the tunnel walls and penetrated into the core through cracks, resulting in contamination. Comparing the CT scan images of conventional perforation with those obtained using the integrated composite perforating system method and analyzing the core perforation profile (refer to Figure 5), it is clear that the integrated composite perforating system reduces the presence of metal residue within the tunnels, improves cleanliness, decreases the skin coefficient, and forms open tunnels with fractures at their ends. The length of these fractures ranges between 40 and 100mm.

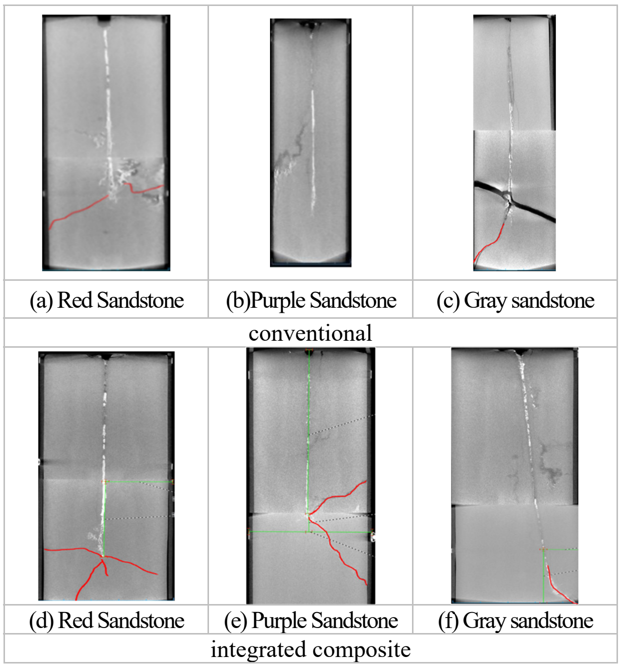

FIG. 4. CT scan of conventional and the integrated composite perforating system

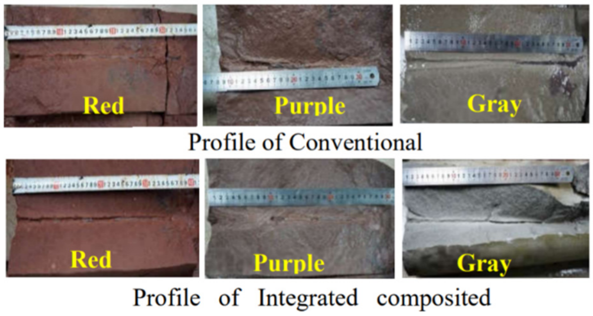

FIG. 5. Comparison of conventional and integrated composite perforating profile

Samples were collected at regular intervals along the perforation tunnel. Using an automatic microscope and a micron-level CNC platform, images were gathered under a multi-field microscope at a magnification of 5×10 to quantitatively measure the micrometre-level parameters of the seam-pore microstructure. The image resolution was 4μm per pixel. The acquired images were then compared to the original rock core for a comparative evaluation of the perforation effect. FIG. 6 depicts the thin-section image of the 80mm diameter rock core casting obtained at regular intervals on the experimental target.

The pore area of each thin section was analyzed and the pore volume fraction was calculated using a fully automatic microscope and a micron-level CNC platform. We then proceeded to analyze and compare the change in the internal pore volume fraction of the rock core resulting from both conventional perforation and the integrated composite perforation system.

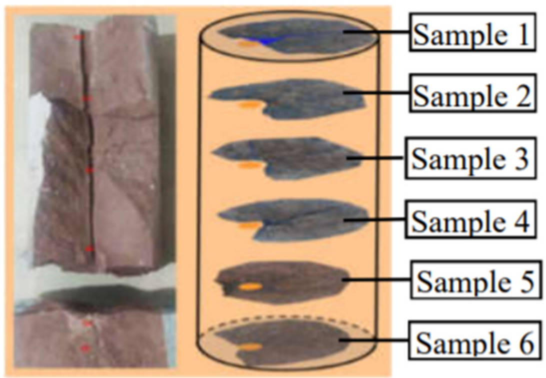

FIG. 6. Thin-sections of an 80 mm diameter obtained at equal intervals on the test target

The specific experimental data can be found in Table 6, Table 7, and Figure 7. According to the analysis of the thin-section results, the integrated composite perforating system demonstrated a 1.34 times improvement in fracture enhancement compared to conventional perforation. This suggests that the integrated composite perforating system exhibits a high energy utilization rate, leading to a secondary effect on the surrounding rock formations. loosening the formation porosity, enhancing the flow coefficient in the near-wellbore zone, and expanding the area available for fluid flow. This is beneficial for increasing well productivity and subsequent reservoir stimulation.

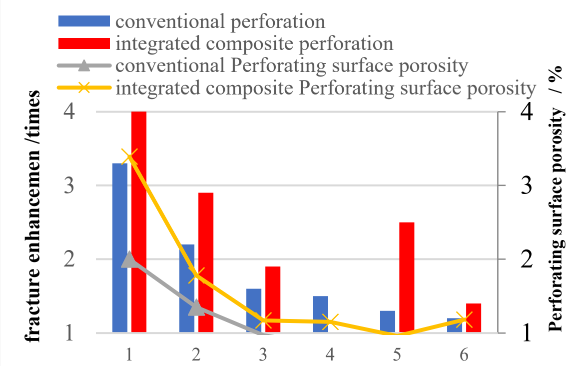

FIG. 7. Comparison of efficiency improvement between conventional and the composite perforating system

Table 6. Microscopic analysis results of test target after conventional perforation

NO.	fracture enhancement	Perforating surface porosity / %	Total number	Mean hole area /μm	Mean maximum pore size /μm	Mean minimum aperture /μm
1	3.3x	2.00	17608	738.3	44.8	23.1
2	2.2 x	1.35	33377	591.1	39.2	20.2
3	1.6 x	0.97	34352	573.7	41.1	21.3
4	1.5 x	0.82	31323	541.8	39.3	19.7
5	1.3x	0.76	33117	477.8	36.1	17.7
6	1.2x	0.80	27870	596.5	39.1	19.8

Table 7. Results of microscopic analysis of test target after perforating with the composite perforation

NO.	fracture enhancement	Perforating surface porosity /%	Total Number	Mean hole area / μm^2	Maximum aperture mean / μm	Minimum aperture mean / μm
1	4.2x	3.39	45457	684.02	44.05	22.75
2	2.9 x	1.78	44945	635.16	43.69	22.63
3	1.9x	1.17	41112	413.64	35.31	16.47
4	Similar	1.15	24948	736.98	46.55	24.00
5	2.5x	0.96	17273	545.77	30.79	15.21
6	1.4x	1.18	21129	354.52	29.23	15.59

4 Conclusion

(1) Simulation tests conducted under reservoir pressure conditions revealed that the presence of a propellant charge interferes with the shaped charge jet, resulting in a decrease of approximately 8% in the penetration depth of the internal composite perforation system compared to conventional perforation. However, the energy released by the propellant leads to a significant improvement in the average flow efficiency of the internal composite perforation system, increasing it by 17.2%.

(2) Analysis of the test target under a microscope demonstrates that the internal composite perforation system produces fewer slugs in comparison to conventional perforation, thereby reducing perforation tunnel damage. Furthermore, multiple extension fractures, measuring between 40mm and 100mm, are generated at the tunnel's end, contributing to the creation of a more loosely formed tunnel.On average, the enhancement effect of perforation and fractures is increased by 1.34 times.

(3) A comprehensive evaluation method for perforation efficiency has been established through the conduction of simulated reservoir perforation tests, flow efficiency testing, CT scanning, and analysis of large-sized thin-section.

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