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Experimental evaluation of near wellbore stimulation – using electrical explosion shockwave on tight sand reservoir

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Abstract. In recent years, the application of electrical explosion shockwave as a stimulation technology is increasing in oil fields, but lacks relevant theoretical knowledge to support it. In view of this problem, a research was carried out on experimental study of electrical explosion shockwave stimulation on the tight sand reservoir to determine the effective range of the resulting effects. An experimental platform for testing electrical explosion shockwave is established. Porosity, permeability and other mechanical parameters of tight sand stone samples are tested before and after electrical explosion shockwave treatment. The result shows clear improvement of the above mentioned parameters and the effective range.

1 Introduction

In recent decades, the proved reserves of low permeability oil and gas have amounted to half of the total proved reserves [1–5] and the low permeability oil and gas reservoirs have become an important part for stable development of Chinese onshore industries. Generally, the inability to produce from low permeability reservoirs at economic rates has prompted the development of stimulation techniques to improve recovery of oil and gas from such reservoirs. Hydraulic fracturing, acid fracturing, thermal and chemical applications as formation stimulation techniques have contributed immensely in improving oil and gas recovery from tight formations. Nevertheless, some formations have not responded effectively to these techniques hence giving rise to the explosive shockwave technology.

The explosive shockwave technology as a supplementary fracturing technique, was introduced into oil industry many years ago. Although it had a better effect on the oil production, it was not widely used because there were many uncertainties which include but not limited to (i) the explosives not being able to detonate successively and repeatedly along the production formation, (ii) the possibility of the explosion damaging the wellbore.

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Until 1980's, an electrical discharge tool was designed to replace the explosive technology for simulating the formations. The most widespread methods of generation of a high-amplitude ultrasound wave is based on its generation by an electrical discharge in water which occurs between two electrodes. In the first phase, an application of a high-voltage pulse leads to an electrical breakdown between a pair of electrodes and a development of a growing streamer which subsequently connects both electrodes. In the second phase, further energy deposition into the formed spark leads to its explosive expansion in the radial direction and the generation of the shock wave in the surrounding liquid. The produced shockwave acts on the rocks and fluids periodically to initiate cracks by its explosive energy. This relieves the stresses in the formation and improves the physical properties and hydrocarbon recovery.

According to Naugol'nykh and Roi [6], the acoustical efficiency of such a discharge (the ratio between the acoustical energy of shock waves and the electrical energy stored in capacitors) can reach 8%, but in many cases can be lower than this value due to complex underground environmental conditions like high temperature and water conductivity. A significant part of electrical energy is spent on the increase of kinetic energy of water molecules and their dissociation. Other processes taking place in a plasma channel, such as evaporation and ionization, consume negligible part of the energy delivered. It would be very difficult to exceed the aforementioned efficiency in the case of electrical discharge in water. Nevertheless, Krasik with coworkers [7] conducted a research of underwater electrical wire explosions using microsecond and nanosecond generators. It was observed that the increase in the rate of energy input into the exploding wire allows one to increase the wire temperature and amplitude of shock waves. Estimated energy deposition into Cu and Al wire material of up to 200 eV/atom was achieved with an efficiency growth of up to 24% in the case of a pressure generated by an underwater electrical explosion of a conducting wire.

Stelmashuk and Hoffer [8] in their work generated shock waves by electrical discharge on composite electrode immersed in water with different conductivities. Their work described the effect of solution conductivity of saline water on the pressure of shock waves. They discovered that the amplitude of shock waves has a nonlinear dependence on water conductivity implying that the amplitude increases with the increase of water conductivity up to 18–20 mS/cm and then decreases again. It was observed that two effects took place; (a) the dependence of the electrical energy dissipated in the discharge on the impedance of the electrode system being affected by water conductivity (b) the strong dependence of the velocity of streamer growth on energy deposition time into the discharge. The result of these two effects is a "hill-like" shape of the curve presenting the dependence of the maximum amplitude of the shock wave on water conductivity.

Tight sand formations as new promising unconventional resources have been stimulated by other techniques in the past. This research presents a new technology for stimulating tight sand formation in order to improve on some physical properties of the formations which can be useful for near wellbore cleaning and as a pre-treatment mechanism for hydraulic fracturing.

In order to be efficient in stimulating tight reservoirs, shockwave explosion technology is in constant review and improvement. From the advent of this technology, shock wave was first generated from the early electrical breakdown in water, it later advanced to electrical wire explosion and now this technology develops to wire electrical-explosion plasma to drive energetic-composite explosion [9–11] as shown in Figure 1.

(1) Shock wave induces electrical breakdown in water

In this technique, generation of shock waves is induced by high voltage breakdown between two electrodes immersed in water. It has some inherent disadvantages: serious energy leakage, low energy conversion efficiency, not stable electrical discharge, interference of temperature and dielectric conductivity. The shockwaves generated are usually not strong enough, so hundreds of shots are needed to achieve a satisfactory fracturing effect. But this will waste time, increase the cost, and, more importantly, greatly shorten the equipment life.

(2) Wire electrical explosion shock wave technology

The wire electrical explosion is the development of the electrical breakdown technology. When an electric wire with a certain length and diameter is placed between the two electrodes of the water gap load, an electrical wire load is created. The mechanism involves the phase transitions caused by electricity. If the storage is enough, the vaporizing discharge passage breaks down forming the arc discharge. Formation of the conducting plasma channel is immediately followed by rapid Joule heating of the channel provided by an external pulsed power circuit. The expansion of the phase explosion and plasma channel pushes the surrounding water outside. Due to the small compressibility of water, it can produce more pressure change compared with air, and produce greater shock waves. The advantage of this technology is the reliability of the discharge, the low requirement of insulation and the high energy conversion efficiency. The limitation is to achieving stable and reliable explosion wire transfer in different application environment.

(3) Wire electrical-explosion plasma drive energetic composite explosion technology

The above two technologies are dependent on the energy storage. However, the well space and energy storage are limited. In order to increase the intensity of shock waves, a wrapped material is put around the wire. Then plasma and strong electromagnetic radiation produced from wire electrical explosion is used to drive the energetic composite explosion. This can increase the magnitude of shock wave energy to ten times. In the process of driving by adjusting the wire and energetic material parameters, safe and controllable shockwave can be generated.

1.1 Mechanism of repetitive pulse shock wave stimulation

In the near wellbore area, direct fractures are generated when the shock wave energy greater than the rock's shear or compressive strength is applied. With increase in propagation distance, the shock wave downgrades to high-strength sound waves, which produces shear force on the interface between oil, gas and water in the reservoir. This strips the blockage attached to the surface of the seepage channel, reduces capillary force and surface tension, improves percolation ability and promotes gas desorption. Repeated action induces fatigue fracture, decreases various mechanical properties and expands the effective area of various functions [12–31].

A number of electrical-explosion shockwaves researches have been conducted since the electrical explosion shockwave was first applied in oil fields. Russian scholars studied the relationship between the operation times of electrical explosion shockwave and the permeability in different lithologic reservoirs. They found that direct application to a sample improved its permeability, and concluded that a higher peak energy can fracture the sample. China University of Petroleum (East China) and China University of Petroleum (Beijing) also carried out series of research on the mechanism of electrical explosion shockwave in different reservoirs. Their research was done in the laboratory with a small experimental device to produce electrical explosion shockwaves and directly apply to the wafer-like samples. The results testified the effect of tearing of the reservoir and plug removal by electrical explosion shockwave.

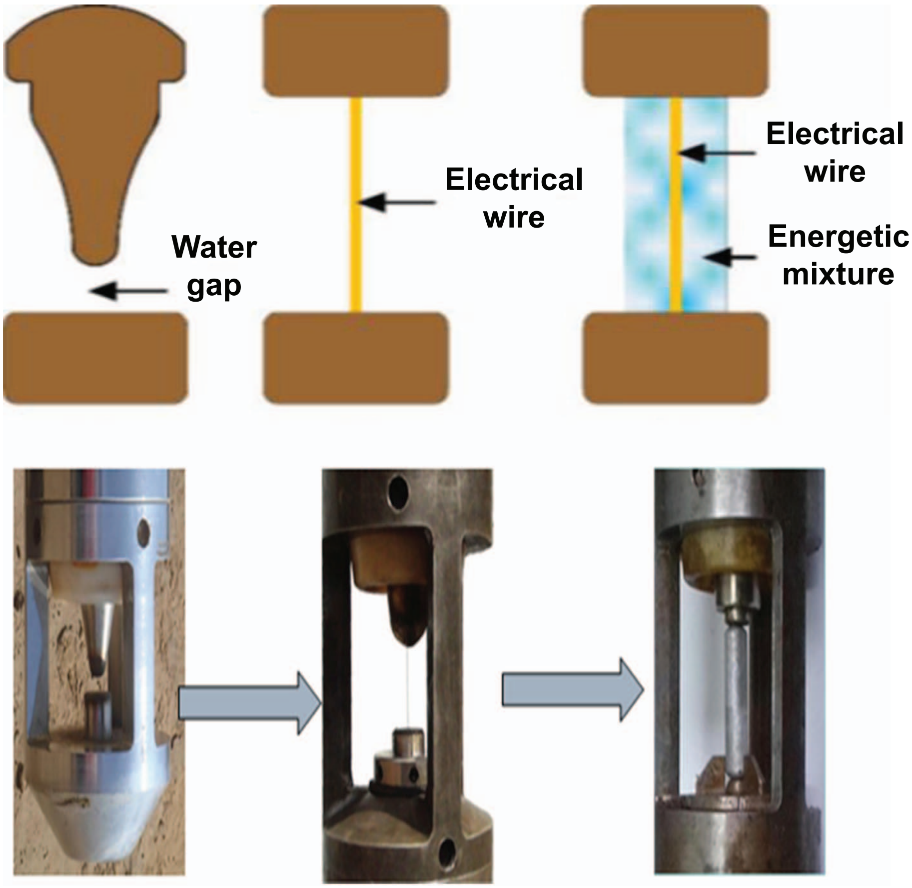

Fig. 1. From left to right: high electrical breakdown converter, electrical exploding wires converter, electrical-explosion plasma drive energetic composite converter.

However, the electrical explosion shockwave loaded to the reservoir penetrated the casing and the cement ring before entering the reservoir. The study of the small samples did not exclude the structural damage of the experimental sample, and other limitations [32–48]. According to the physical characteristics of the electrical explosion shockwave and reservoirs, the electrical explosion shockwave with the effect of tearing and plug removal can effectively improve the reservoir permeability. However, these theoretical analyses need to be experimentally verified particularly the effective range of these effects will determine the adaptability of this technology.

This paper presents a research on electrical explosion shockwave stimulation of tight sand reservoir. It is motivated by the fact that previous works only considered the improvement of reservoir physical properties by the explosion shockwave. Therefore the main aim of this work is to determine the nature of shock wave propagation and effective range (extent) of the electrical explosion shockwaves in the reservoir after penetrating the casing and cement ring. Thereby determining the magnitude of the improvements caused by the electrical explosion shockwave stimulation. This will provide basis for theoretical support in engineering applications [49–61].

2 Experiment

2.1 Experimental apparatus

The schematic diagram of electrical explosion shockwave system is shown in Figure 2 which we used to generate shock wave. The system contains $\phi 990 \times 1300$ mm experimental container, 30 kJ electrical explosion shockwave generating device (Independent developed, has been applied in field operations), a GTEB4.5-3.0 Power controller, CS-1D Super dynamic strain gauge (band range of 0–1 MHz), DPO4014B Oscilloscope, PCB and PVDF pressure sensor, high frequency dynamic strain gauges. Perforation density is 16 per meter and perforation diameter is 12.7 mm.

2.2 Test samples

The samples as shown in Figure 3 are tight sand cores of dimensions $\phi 50 \times 300$ (diameter $\times$ length) which are outcrops collected from large samples of diameter 600 mm, height 600 mm with a 220 mm diameter hole at the center from Sishilipu field, Suide. Figure 4 is a small sample of 50 mm in diameter for mechanical parameters test.

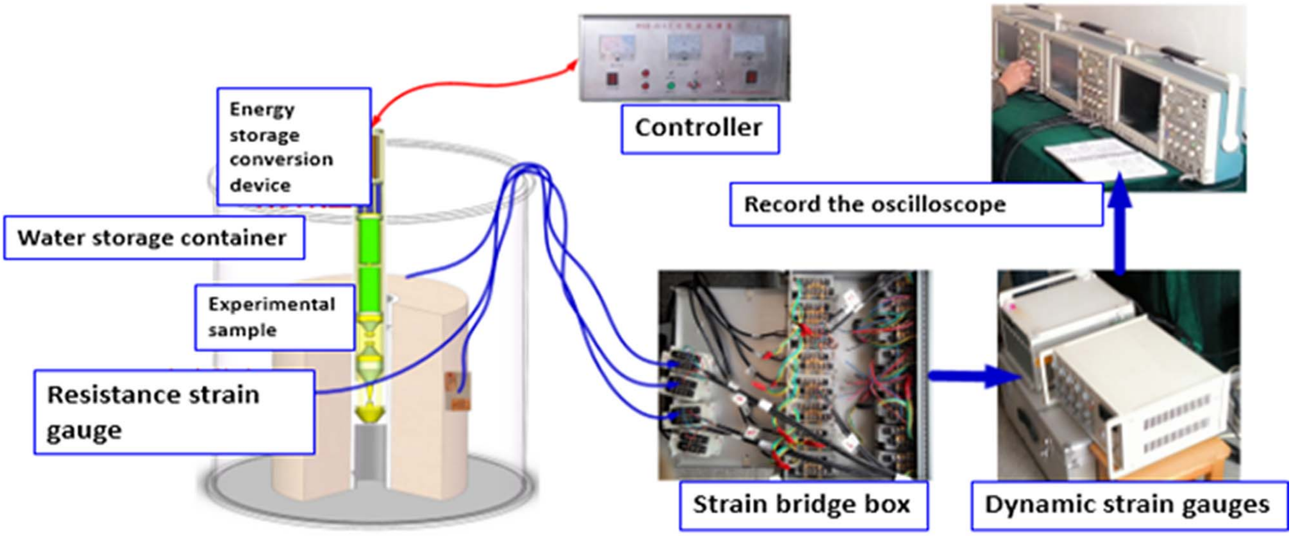

Fig. 2. Experimental flow chart.

Fig. 3. Chang-6 sandstone sample.

Fig. 4. Columnar sandstone sample.

2.3 Experimental procedure

(1) Sandstone fracturing test:

A large sandstone sample is placed in the water storage container, then electrical explosion shockwave is generated at the centre of the sample with casing, connected to the power controller. The sample is put into the water integrity.

(2) Electrical explosion shockwave parameter measurement:

Based on the fracture test, the strain gauge is attached outside the large sample and the strain bridge box, then dynamic strain gauge and oscilloscope are connected in turn as shown in the experimental procedure setup is shown in Figure 2.

The measuring system is grounded and shielded from electromagnetic field signal. A diode limiter and fast bypass circuit are set in the strain gauge measurement circuit. The strain gauge is pasted in considerations to waterproof and anti-electromagnetic interference.

PBC probe is applied to the measurement of shockwave parameters on the experimental platform before the experiment. The measurement results obtained are used to simulate the borehole according to the propagation characteristics of shockwave. As for the outer side, the PVDF film probe is pasted to measure the radial shockwave parameters. Dynamic strain gauges were also pasted on the outside of the experimental sample in lateral and longitudinal methods. The lateral sticking method is used to measure the angular strain and the longitudinal sticking method is used to measure the axial strain.

2.4 Experimental results

After the experiment, it was observed that the core exhibits cracks in four directions of the entire sample's outer surface as shown in Figure 5 and the entire sample ruptures into three parts as in Figure 6. The strain waveform shape shows that the measured points have significant residual strain.

Fig. 5. Outer surface cracks in four directions.

Fig. 6. Samples broken into three parts.

Some strain gauges in the fissure area were damaged, and no data was retrieved.

Waveform results in source area

The waveform measured on the simulated borehole surface is shown in Figure 7. This waveform can be controlled by adjusting the operating parameters of the electrical explosion device.

Strain measurement results

The circumferential strain waveforms of the dynamic strain gauges affixed to the sample's outer edges are shown in Figure 8. The axial strain waveforms measured from the longitudinal strain gauge are shown in Figure 9.

Comparing Figure 8 with Figure 9, obvious differences exist between the strain waveforms measured from axial and that from circumferential strain gauges. The tensile effect is measured by the circumferential strain gauge, and there was no shrinkage effect recorded while the axial strain gauges obviously recorded shrinkage effect. The propagation of shockwave along the radial direction is different from that along the longitudinal direction.

Porosity-permeability and mechanical parameters test results

Core samples sharing the same number are collected from the same point. Close observation shows that there are changes in the core sample's parameters after electrical explosion shockwave treatment. Porosity, permeability test results are shown in Table 1. The mechanical parameters results are shown in Table 2.

This paper uses the clean and dry core to measure the porosity-permeability data, which excludes pore fluid interference factors. Therefore, the main factor for changes of porosity and permeability is the effect of shockwave.

According to the theory of shockwave tensile failure, the rock fracture tensile damage often occurs first. The stress wave acting on the rock sample results in a certain number of fissures or micro-fractures in samples. The mechanical

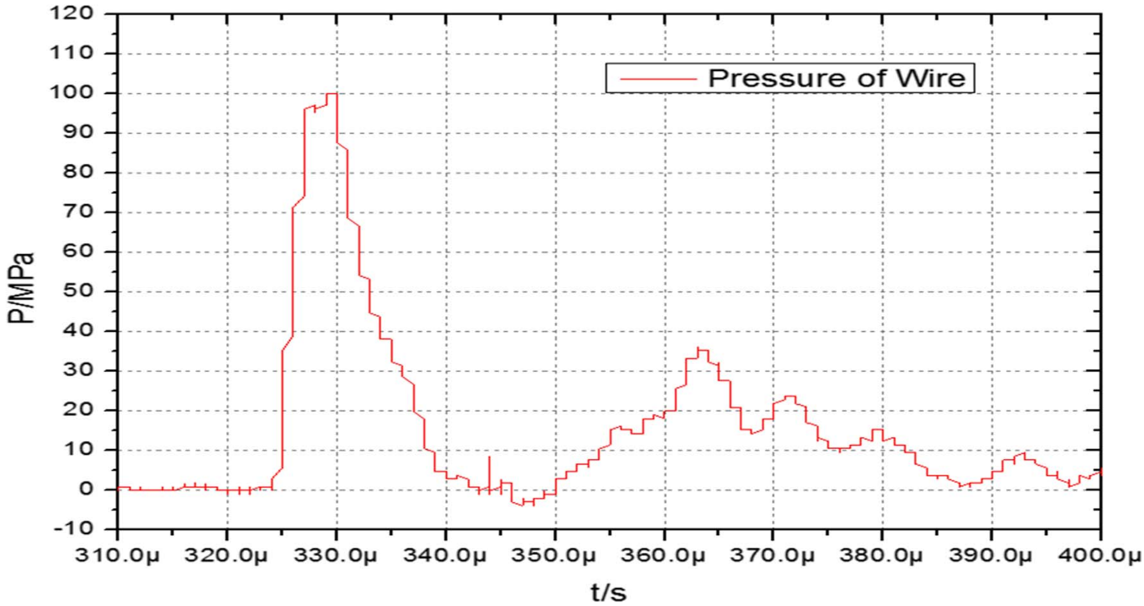

Fig. 7. Electrical shockwave form.

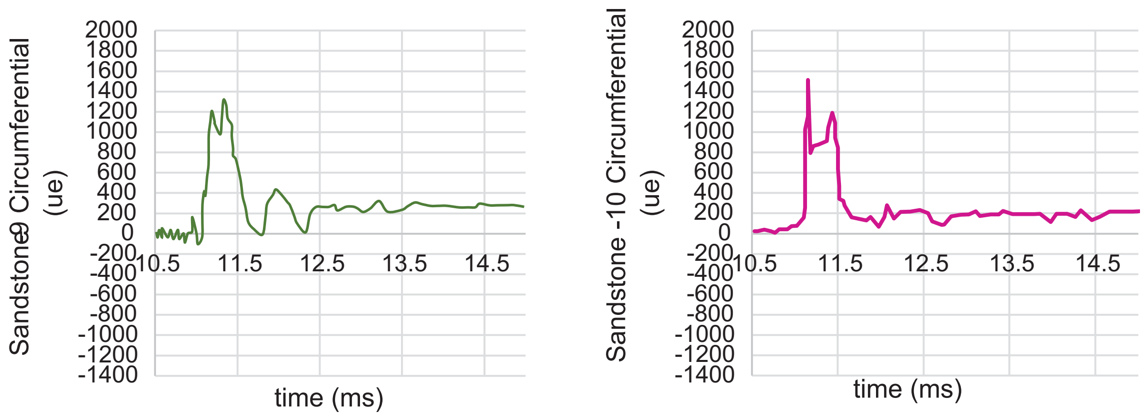

Fig. 8. Ring strain measurement results.

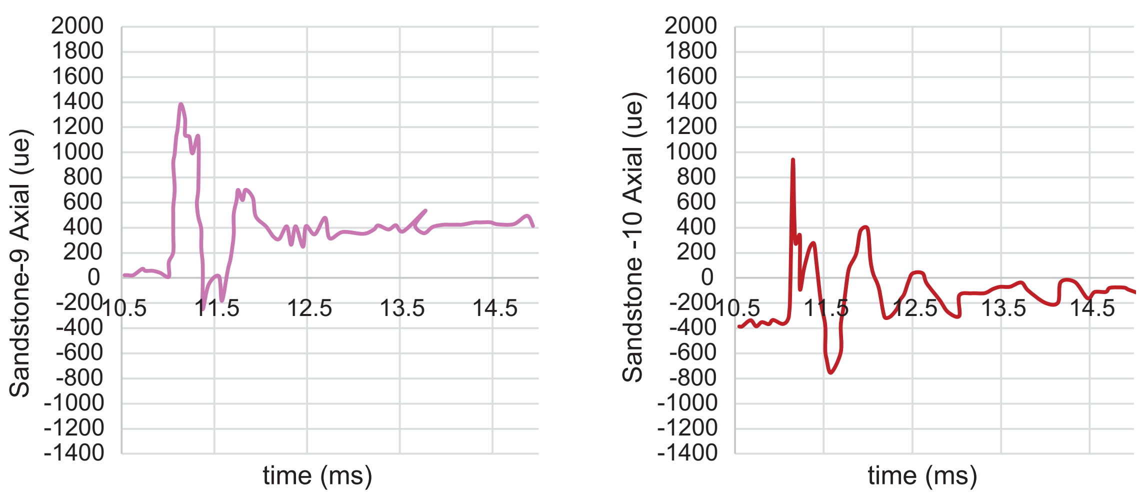

Fig. 9. Axial strain measurement results.

Table 1. Pore permeability test results.

Number	No electrical explosion shockwave effect on samples				Electrical explosion shockwave effect samples			
	Length (cm)	Diameter (cm)	Permeability (10^{-3} μm^2)	Porosity (%)	Length (cm)	Diameter (cm)	Permeability (10^{-3}μm^2)	Porosity (%)
1	3.600	2.536	0.70800	15.50	3.276	2.520	4.39721	16.08
2	2.830	2.532	0.74300	15.61	3.178	2.520	3.37309	15.42
3	3.562	2.520	1.57900	14.57	3.158	2.520	2.47621	15.70
4	2.952	2.500	1.72451	14.69	3.160	2.510	2.18007	15.02
5	3.100	2.484	3.13729	15.96	3.200	2.500	2.13031	15.38
6	3.170	2.500	2.54551	15.22	3.214	2.462	2.50613	15.16
7	3.200	2.500	2.25601	15.56	3.200	2.430	2.76595	15.89
8	3.058	2.480	1.54816	15.06	3.310	2.456	1.38981	15.22
9	3.118	2.500	2.24993	16.10	3.268	2.420	2.03809	15.95
10	3.060	2.472	2.18654	15.80	3.336	2.460	2.35937	16.21
11	3.140	2.484	1.60323	14.37	3.284	2.472	1.38055	15.33
12	3.100	2.472	0.70869	14.43	3.226	2.482	2.60816	16.09
Average	3.158	2.498	1.75000	15.24	3.234	2.479	2.47000	15.62

Table 2. Mechanical parameters test results.

Category	Compressive strength		Tensile strength (MPa)	Elastic modulus (GPa)	Shear strength		
	Dry (MPa)	Saturation (MPa)			Poisson's ratio	Cohesion (MPa)	Coefficient of friction
No electrical explosion shockwave effect	50.81	45.39	2.85	4.79	0.22	4.03	0.68
After electrical explosion shockwave treatment	34.43	28.78	1.73	3.13	0.25	2.88	0.65

strength of the rock is reduced, the fissures and micro-fractures are extended with the increase of the shockwave number.

The results obtained from this experiment are the key parameters for numerical simulation, which are important basis for guiding and modifying numerical simulation results.

3 Conclusion

In this paper, we studied the propagation of explosion shockwave and the effective range of changes in permeability, porosity and mechanical properties of the tight sand core samples caused by electrical explosion shock wave stimulation. From the results obtained, it can be concluded that;

- Electrical explosion shockwave generated was able to penetrate the casing to crack the tight sandstone in a fracturing mode rather than in a broken pattern.
- Because there was no artificial contamination, the increase of porosity and permeability after the experiment were mainly caused by micro-fractures. In the area of no visible fracture, mechanical parameter change of the samples was due to micro-fractures induced by the shockwave.
- Permeability increase was relatively higher in the low permeability region due to the isotropy propagation characteristic of shockwave.
- There were obvious differences between the strain waveforms measured from axial and circumferential strain gauges. The propagation of shockwave along the radial direction was different from that along the longitudinal direction.

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