Physics Letters A ••• (••••) •••–•••

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Discussion

Influence of water conductivity on shock waves generated by underwater electrical wire explosion

Ben Liu [a], Deguo Wang [a,b], Yanbao Guo [a,b,*]

[a] College of Mechanical and Transportation Engineering, China University of Petroleum, Beijing 102249, China
[b] Beijing Key Laboratory of Process Fluid Filtration and Separation, Beijing 102249, China

ARTICLE INFO

Article history:
Received 23 February 2017
Received in revised form 16 October 2017
Accepted 18 October 2017
Available online xxxx
Communicated by F. Porcelli

Keywords:
Electric explosion
Shock waves
Water conductivity
Enhanced oil recovery
Energy deposition

ABSTRACT

The new application of electrical explosion of wire (EEW) used in petroleum industry is to enhance oil recovery (EOR). Because of the complex environment underground, the effect of underground water conductivity on EEW should be considered. This work describes the effect of water conductivities on discharge current, voltage and shock waves. It was found that the effect of water conductivity contains two parts. One is the shunt effect of saline water, which can be considered as a parallel load with the copper wire between the electrodes connected to the discharge circuit. The peak pressure of shock waves are gradually decrease with the increase of water conductivity. The other is the current loss through saline water directly to the ground ends without flowing through the electrodes. The shunt effect is the main factor affecting the wire discharge process. As the charging voltage increased, the energy loss caused by these two parts are all reduced. These indicate that increasing the charging voltage to a certain value will increase the energy efficiency to generate a more powerful shock waves in conductive water.

1. Introduction

In petroleum industry, the developing of stimulation techniques to improve recovery from low-permeability oil and gas reservoirs is an important project. Hydraulic fracturing, acidizing, and chemical applications have contributed significantly to improve oil recovery, but some formations have not responded to these techniques. The explosive technology, as an adjuvant fracturing technique, is introduced into oil industry early to 100 years ago to resolve these matters, and the nuclear explosives used in oil and gas production had been widely studied at around 1960s [1–4]. Although it has a better effect on the oil production, it is not widely used because these are many uncertainties, such as the nitroglycerine pharmacy was too sensitive and dangerous in transportation, the explosion may damage the wellbore and the effective ways to detonate the explosives are needed. What is more, the explosives cannot explosion successively and repeatedly along the production formation. One of the biggest problems in the use of nuclear energy is the public concern for radiation hazard.

Until 1980's, an electrical discharge tool is designed to replace the explosive to simulate the layer. This downhole tool is based on the hydro-electric effect and it can generate the shock waves (SWs) by electrical discharge through a water gap. Compared with the method of explosives, this tool use a convenient, stable and controllable way to generate the SWs. These SWs act on the rock and fluid in stratum periodically through the perforations and it does not need to apply the chemical or biological agents that are harmful to the environment. However, this technology also has some inherent disadvantages. The most serious defect is the low energy efficiency of such a discharge which the energy of shock waves only can reach 8% of the electrical energy stored in capacitors [5]. In order to generate a strong shock wave, the volume of energy storage unit has always be large, and it limits the applicability of this tool. What is more, the discharge may also be unstable under the complex environment underground, like the high temperature and water conductive. In accordance with Vitaliy Stelmashuk and Petr Hoffer [6], the water conductivity has a great effect on the amplitude of these shock waves, and they are nonlinear dependence.

Starting from the 1980s when the electrical discharge tool first proposed to use shock waves for stimulating the production layers and up to now, a significant part of experimental studies of this electrical discharge tool are focused on energy efficiency and miniaturization [7–10]. During recent years, the researchers change the load of this system. They put a conducting wire between the two electrodes to instead of the water gap. It is reported that the efficiency growth of up to 24% in the case of a pressure generated by an underwater electrical explosion of a copper wire [11].

* Corresponding author at: College of Mechanical and Transportation Engineering, China University of Petroleum, Beijing 102249, China.
E-mail address: gyb@cup.edu.cn (Y. Guo).

https://doi.org/10.1016/j.physleta.2017.10.039
0375-9601/

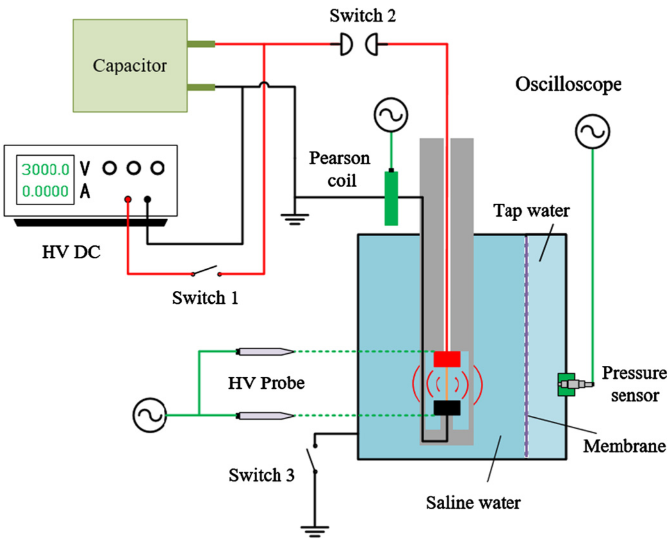

Fig. 1. Schematic diagram of the wire explosion system.

The electrical explosion of wire (EEW) is gradually acted as a physical and environmentally friendly adjuvant EOR technology in petroleum industry [12,13], and the pressure amplitude is allowed to be tens of megapascal to simulate the layer in our laboratory results. This amplitude is the pressure in a certain distance from the wire core. The distances depend on the diameter of casing pipe. There have been some studies on these SWs. Grigoriev [14] discussed the inductance of the discharge circuit affecting on SWs. The result showed that the peak pressure decreases with the increase of inductance. A. Grinenko [15] discussed the maximum pressure generated by underwater electrical explosions of Al and Cu at the DC boundary vs different parameters. They found that there is a poor correlation of peak pressure with total deposited energy and the deposited energy per atom. However, a good correlation with the deposited energy per unit length. The propagation of SWs had also been tested in water, which is decreased along with the propagation distance by exponential decay [16,17]. In order to generate strong converging shock waves, the electrical explosion of a single wire is replaced by the wire array with different structures, including zigzag wires [17], ring-shape wires [19], planar wire arrays [11], cylindrical wire arrays and spherical wire arrays [20,21], but these wire arrays are inapplicable to be installed in our downhole tool. Because once we put this downhole tool into the casing pipe underground to simulate the layer, the pressure of SW should not be too larger in order to ensure the integrity of casing pipe and cementing sheath. It is more effective to use a reasonable SW pressure and repeated explosions to simulate the layer. Therefore, a wire feeding system is needed to deliver the copper wire automatically. The structure of wire must be simple, easy storage and transportation, and a single straight line is a good choice.

The main parameter of EEW in our application is the amplitude of shock waves. As discussed above, the researchers pay more attention to the circuit parameters, the influence of explosion environment are rarely discussed. However, in our application, the environment of the wire explosion underground is very complex. This may have an impact on discharge, thus affecting the generation of shock waves. This paper is aim to discuss the effect of water conductivity, which is one of the important environment conditions in production layer, on shock waves generated by underwater EEW. The conductivity of underground water is not only effect by a number of mineral but also effect by the project of water injection and hydraulic fracturing.

2. Experiment setup

The schematic diagram of wire explosion system is shown in Fig. 1, which we used to generate the shock waves. This system contains two circuits. The one is the charging circuit, which the capacitor is charged by a high voltage power supply. The other is the discharge circuit, which made a high voltage and pulse current apply to a thin wire made of copper. The capacitance C of capacitor is 30 μF. The stray inductance L_c and the resistance R_c of this discharge circuit without wire load are 5.27 μH and 93.2 mΩ, respectively. The discharge load is placed in a water tank filled with saline water. This tank is divided by a waterproof sound-permeable membrane into two parts. The conductive part is filled with highly conducting saline water. To protect the pressure gauge from being burned out by the pulse current, the other part, which is connected the pressure gauge at its edge, is filled with tap water. The load of copper wire placed between the two electrodes is 25 mm in length and 0.2 mm in diameter. This is not only to ensure the stability of wire feeding, but also to match the energy storage of this downhole tool which can generate a suitable SW pressure and ensure the integrity of casing pipe and cementing sheath. The enthalpies of copper wire phase transformation from solid state to liquid, vaporization and the atomization enthalpy are 10 J, 32.88 J and 42.88 J, respectively [22]. The discharge waveforms of current $I(t)$ and voltage $U(t)$ were measured by a commercial Rogowski coil, Pearson 101, and two high voltage dividers. These data were acquired by a Keysight DSO-X 2014A 4-channel digital oscilloscope.

The gauge used in measuring SW is a 109C11 type pressure gauge produced by PCB Piezotronics Inc., which is widely used in the blast tests [16,23]. Because of the strong electromagnetic interference during the discharge process and the exposure time affected by a residual voltage on the capacitor bank, a simple and effective way to avoid the sensor under exposure of an electric field is to adjust the moment when the shock wave arrives. The pressure gauge with flush mount installation, which is no reduced area passage from the gauge diaphragm to the test shock waves, is placed at about 150 mm away from the wire center and its fit for these tests.

3. Results and discussion

3.1. Effect of water conductivity on discharge process

Fig. 2(a) shows the pressure waveforms of shock waves measured in 150 mm away from the wire core under the different charging voltages, and they generated by the copper wire explosion in tap water with a conductivity of 0.6 mS/cm. Two charging voltages U of the capacitor are tested and the energy stored in capacitor can be calculated by $W = 0.5CU^2$. These energies are 135 J and 345.6 J under the charging voltage of 3 kV and 4.8 kV. Because of the high current rise rate under the charging voltage of 4.8 kV, the energy is deposited more quickly into the wire. The explosion time, which can be considered to be at the moment of the peak voltage (Fig. 3(a) and (c)) [24,25], is a little early under the higher charging voltage, and this results the time difference of the peak pressure in Fig. 2(a). The positive amplitude of these two shock waves reaches 35.5 MPa and 27.5 MPa, respectively. Because of the SW reflection from the walls of tank, the pressure waveforms sustained oscillation. Pressure amplitudes measured in different water conductivities are shown in Fig. 2(b). Although, the peak pressure decreases with the growth of water conductivity, the water conductivity seems has more effects on the discharge of charging voltage of 3 kV. What is more, when water conductivity up to 26.7 mS/cm, the peak pressure is fluctuating around 28 MPa under the charging voltage of 4.8 kV.