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Study on the interaction mechanism between laser and rock during perforation

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ABSTRACT

In this paper, we describe the experimental laser perforation of rock. The different depth of laser penetration in the experiment demonstrated that the most important variables affecting perforation were laser power and irradiation time. The interaction mechanism between laser and rock during perforation was investigated. This investigation was conducted using an optical microscope, high-speed video images, X-ray diffractometer and other methodologies. The results indicated that the vapor/plasma of laser perforation was in a mutative process, displaying that complicated physical and chemical reactions were proceeding. A change in the molten pool during laser perforation was dynamic over time, involving heat transfer, heat radiation and instantaneous phase transition. Overheated energy in the molten pool led to material spatter which spilled from the perforation, a result of the recoil pressure of atomic vapor. XRD results revealed that the phases of rock after perforation mainly consisted of SiO_2 and Fe_2O_3. During laser perforation, by employing either a continuous zooming process with a side blow or increasing the number of laser perforation passes with a side blow can significantly increase the depth of laser perforation.

1. Introduction

In the petroleum industry, perforation is necessary to achieve the exploitation of oil and gas. Perforating is a method of making holes through the cemented steel casing and the surrounding rock formation to allow oil or gas to flow into the well. Generally, underbalanced perforating [1,2], deep penetrating perforation [3], abrasive water jet (AWJ) perforation [4], and explosive charge perforation [5,6] are used to fracture the rock. These methods risk serious problems such as rock formation damage, high cost, oil pollution, etc., all of which limit their use.

A considerable number of research studies of perforation have been conducted with the objective of improving recovery of oil and gas. Behrmann et al. [7] determined that the primary cause of wellbore damage in perforated completions was invasion of pulverized formation rock grains and the resulting low-permeability crushed zone. Grove et al. [8] found that perforation depth was generally related to the formation effective stress and that increasing pore pressure increased penetration. Jan et al. [9] concluded that creating a dynamic underbalance in the well that would deliberately induce flow into the wellbore for tunnel cleanup minimized this type of damage during the perforating process. Keshavarzi [10] demonstrated that explosive shaped charge perforating methods may require costly post-perforation operations and produce formation damage which results in reduced permeability.

Fracturing initiated by fluid pressure during perforation has proven to be beneficial in enhancing the production of oil and gas wells. The perforation geostress mechanical model was investigated by Wang et al. [11]. Their research demonstrated that low-permeability reservoir geostress distribution of different stages determined the fracture initiation position and fracture pressure, taking into account the rock failure criterion.

Conventional perforation methodologies limit rapid development of the petroleum industry, depending as it does on stratigraphic conditions and mining tools. New perforation methods are urgently needed to accelerate development of energy resources. Growing interest in the field of material science in possible benefits arising from the use of newly developed high-power fiber lasers (HPFL) for materials processing gives rise to interest in expanding the scope of its use. Major advantages of these type of

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lasers include better absorption, beam quality and electrical efficiency [12].

Considering the above characteristics, new lasers are believed to have great potential in the field of petroleum production. This new approach employing advanced high power laser technology provides a new alternative to conventional perforating methods. Laser technology applied to perforation is attractive primarily because of its potential to reduce perforating time. Since it does not come into direct contact with the rock, the need to stop periodically to replace a mechanical bit is eliminated. Additionally, when using laser technology for perforation, the rock is left cleaner and fluid flow paths for oil and gas production suffer less damage, both significant advantages over other methods. As a result, the high costs of operating a drill rig is significantly reduced. However, one of the challenges in laser perforation was the laser beam-fluid interaction that resulted in laser power loss (LPL) [6].

High power laser perforation is a promising new technology in the oil industry with the potential to overcome such problems. The basic mechanism of laser perforation uses a high energy beam to rapidly heat the local rock matrix material, instantly causing transition from the solid phase into the melting and vaporizing phase, then forming a gas/liquid/solid multiphase mixture. The mixture is subsequently removed by high voltage auxiliary air. The depth of laser perforation is mainly determined by laser power and power density, while improvement in rotary bit drilling in the stratum depends on new materials and better design [13].

The purpose of this research is to study the mechanism of interaction between laser and rock during perforation. During this process, the vapor/plasma and molten pool were investigated using high-speed video images to analyze complex changes. The phases of rock after laser irradiation were also examined to determine the cause of change in rock performance. Concurrently, the viability of high power laser perforation has been further explored.

2. Experimental procedure

2.1. Experimental equipment and materials

The experimental laser is a Ytterbium Fiber laser, YLR-10000. The main technical parameters of this laser are as follows: lens focal length of 300 mm, focal point diameter of 0.48 mm, emission wavelength of 1.07 μm and normal output power of 10 kW. The experimental materials are sandstone, the heat physics parameters and mechanical parameters of which are described in Table 1. Samples were all the same dimension of 200 mm × 200 mm × 150 mm. The composition of the sandstone used is SiO_2, CaO, Al_2O_3, MgO and a small amount of air.

Perforation with a high-power fiber laser (HPFL) was performed on the sandstone using three variables: laser power, irradiation time and focal point position. The laser head was mounted on an industrial robot (ABB), which drove the laser head over the clamped sheets at the desired speed. The samples were firmly fixed flat on the workbench so that the laser beam was perpendicular to the surface of the work piece. Optical defocus was carried out to prevent material spatter from damaging the lens during laser perforation. The laser perforating setup is pictured in Fig. 1.

Table 1
Heat physics parameters and mechanical parameters.

Material	Parameters	Units	Levels
Sandstone	Density	g/cm^3	2.0
	specific heat capacity	J/(g K)	0.75
	Heat conductivity	W/(m K)	4.4
	Young ' modulus	GPa	15
	Line expand coefficient	K^{-1}	5.6×10^{-6}
	Poisson ' ratio		0.12
	Anti-press strength	MPa	110
	Anti-tensile strength	MPa	25
	Heat of fusion	kJ/g	1.8
	Heat of gasification	kJ/g	13.7

2.2. Experimental design

Trial and error was used to identify parameters affecting the laser perforation process that could produce an acceptable perforation at the longest irradiation time possible for each power level. A preliminary experiment was conducted on a material thickness of 150 mm to ascertain the optimum focal point position. The objective was to achieve the highest depth of perforation for a certain parameter, while protecting the lens from damage. After a visual examination of the perforation and macrographs of the preliminary test samples, an experiment was carried out using the most promising parameters to confirm that those parameters resulted in a perforation of acceptable quality. A defocusing value of 40 mm was confirmed by the preliminary experiments. Perforating three times are performed under the condition of each process. In order to take the mean to eradicate any discrepancies, the average of observed data is deemed to be the depth of perforation. Process variables of laser perforation are listed in Table 2. The waveform of high-speed video in the experiments is shown in Fig. 2.

3. Results and discussion

3.1. Morphology of perforation

The typical morphology of laser perforation is shown in Fig. 3. Depth of perforation under different parameters is listed in Fig. 4. The technology parameters are as follows: laser power of 4 kW,

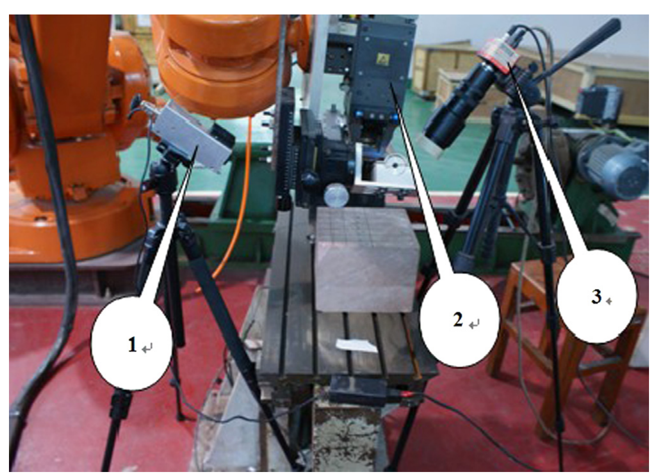

Fig. 1. Laser perforating setup: (1) illumination, (2) laser head and (3) high-speed video.

Table 2
Process variables of laser perforation.

Equipment	Variables	Units	Levels
YLR-10000	Laser power	kW	1, 2, 3, 4
	Irradiation time	s	1, 3, 5,10, 15
	Focal point position	mm	40