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A laboratory study about laser perforation of concrete for application in oil and gas wells

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ABSTRACT

Laser perforation is the application of light to make a flow path between wellbore regions through the casing wall and cement layer all the way to reservoir production zone. Due to significant losses of laser power at long distances, introducing a novel method in order to facilitate laser perforation in oil and gas reservoirs is necessary. This paper aims to study on concrete perforation using a continuous 240 W/cm^2 CO_2 laser. In this research, the effect of water on the parameters of laser perforation such as rate of perforation (ROP), specific energy (SE) and dominant mechanisms was investigated. For this, two groups of concrete samples (dry and wet) were illuminated at 2, 6, 15, 30 and 60 s by the laser. Our results showed evaporation was main mechanism for dry samples at exposure times above 15 s, while spallation was the dominant mechanism for the wet samples at all exposure times. ROP and SE were significantly increased and decreased in the presence of moisture, respectively. Maximum ROPs obtained 2.26 mm/s and 0.45 mm/s for wet and dry samples, respectively. Also, minimum of SEs for wet and dry samples obtained 1.05 J/mm^3 and 4.3 J/mm^3, respectively. Finally, our experimental results were justified using a simplified heat conduction model. All these characteristics demonstrate presence of water in concrete possesses an important role to improve rate of laser perforation. Therefore, the results of this research could significantly reduce time and cost of laser perforation for application of oil recovery.

1. Introduction

Nowadays, lasers due to their unique properties such as high intensity and low divergence are widely used in a wide range of industrial applications. Several researches were performed in order to replacement of traditional perforation by laser methods in petroleum industry (Price, 1980; Salisbury and Stiles, 1980; O'Brien et al., 1999; Gahan et al., 2001; Figueroa et al., 2002; Batarseh et al., 2003; Gahan et al., 2004; Xu et al., 2004a). Laser perforation involves creating a flow path between the reservoir and the wellbore for the inflow of the reservoir fluid to the wellbore. Some of the advantages of laser perforation over conventional methods include low energy consumption, remote energy delivery employing optical fibers, working days reduction, control of hole geometry, reduction of costs, and significant increase in perforating speed (Pooniwala, 2006). Application of laser in petroleum reservoirs has been successfully studied by a number of researchers. For example, Xu et al., 2004b observed that fractures were created in rock by a pulsed 1600 W Nd:Yag laser and consequently they reported an increase in ROP. Also they reported that illumination of shale rock by a pulsed1600 W Nd:Yag had a maximum values about 8.1 cm/s and 520 J/cm^3 for ROP and SE, respectively. Also, in the other experiment by Xu et al., 2009, radiations of a 6 kW super pulsed CO_2 laser on limerock improved ROP to 1.83 cm/s and SE to 5100 J/cm^3.

Three mechanisms contribute in laser perforation: spallation, melting and evaporation (Moavenzadeh et al., 1967; Farra et al., 1969). In spallation, absorption of energy from high power laser radiations causes a momentary temperature growth in rock. Thermal tension induced by laser may cause fractures in rock below melting point. In laser perforation of concretes, when power density of laser beam is high enough, temperature rises to melting point and a glassy layer is formed on concrete surface. This glassy layer has a bond strength which is almost $\frac{1}{3}$ smaller than that of the untreated concrete surface (Lawrence and Li, 2000; Rao et al., 2005). Vaporization also can be realized at long irradiation of high power lasers on the surface of melted concrete.

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Normally, in the process of laser perforation, some parameters such as specific energy (SE) and rate of perforation (ROP) are mainly considered. Specific energy (J/cm^3) is required energy for removal of unit volume of concrete and is calculated using the following equation (Xu et al., 2003, 2004b):

$$SE = \frac{P \cdot t}{\left(\frac{m}{\rho}\right)} \tag{1}$$

where P is power of laser, t is time of laser illumination, m is change in the mass of concrete and ρ is density of concrete. Moreover, ROP (cm/s) is given by the following equation (Xu et al., 2004b):

$$ROP = \frac{SP}{SE} \tag{2}$$

where SP is the laser power density (W/cm^2). The amount of ROP and SE depends on properties and parameters of laser and rock (Gahan et al., 2001; Batarseh et al., 2003; Ahmadi et al., 2011). For example, Gahan et al., 2001 reported that for each type of rock there is a set of optimal laser parameters to minimize specific energy values.

However, perforating in petroleum reservoirs presents several challenges. For example, at high laser intensities, melting and evaporation are the main mechanisms of laser perforation (Xu et al., 2005) because a considerable portion of the absorbed energy is spent to change the phase of sample. As a result, melting and evaporating cause a significant increase of SE and subsequently a considerable ROP reduction.

Also, the formation of microfractures through spallation needs to lower amount of SE (Xu et al., 2004b). Therefore, avoiding melting and evaporation is necessary in order to improve performance of lasers on perforating applications. Also, laser power significantly attenuated due to scattering and absorption of light in optical fiber (Mahto et al., 2012). However, yet there are no report on mechanism controlling for laser perforation, so it is necessary to improve parameters of laser perforation through spallation mechanism. Also, the effects of moisture on laser perforation of stone have little been studied (Ahmadi et al., 2011). Therefore, this paper attempts to fill the gap.

2. Materials and methods

2.1. Preparation of concrete samples

First, several samples of light concrete were made by mixing Portland cement; 20 kg, leca; 22.22 kg, rock powder; 4.44 kg, silica; 4.44 kg, silicon oil; 0.45 kg and water 8 kg (Taylor, 1997). Then, two groups of cubic concretes (10 × 10 × 10 cm^3) were prepared. Samples of groups I and II were submerged in distilled water and water of city (Babol city, specific heat of 4182 J/kg.K, thermal conductivity of 0.6 W/m.K, hardness of 353 ppm and electrical conductivity of 706 μs/cm) for 28 days, respectively (Xu et al., 2009). After this time, samples of group I were completely dried at 100°°C for 24 h in order to achieve 0% as the degree of water saturation. But, samples of group II (wet group) were pulled out of the water and without drying (15% water saturation) were sent to investigate the roles of moisture on the parameters of laser perforation.

2.2. Laser perforation experiments

In these experiments, a continuous homemade CO$_2$ laser (30 W and spot diameter 4 mm) was used to exposure the surface of the samples at different illumination times (2, 6, 15, 30 and 60 s). The experimental set up has been shown in Fig. 1. A visual study of perforated concretes was performed by a digital camera and after that size of produced holes was measured. Our experiments were repeated three times for each test and standard deviations were calculated.

3. Results and discussions

3.1. Investigation of water effect on laser perforation

In these experiments, illumination of groups I and II was performed at different exposure times by the irradiation of a 240 W/cm^2 continuous CO$_2$ laser. The results for group I have been summarized in Table 1. According to Table 1, the maximum and minimum rate of perforation are attributed to 2 and 60 s exposure times, respectively. Fig. 2a shows photographs of these results. As seen in this figure, melting did not occur at 2 and 6 s, in other words, the concretes were perforated by spallation mechanism. Based on our observations, perforation in samples with illumination times more than 15 s is related to evaporation of concrete surface. Moreover, melting was also observed after 15 s illumination and a glazed layer formed on the surface of concrete.

Fig. 2b shows photographs of produced holes in wet concretes. According to the figure, a thin glazed layer was also seen on the surface of the concrete for all exposure times. The glazed material was subsequently removed by mechanical means and after that, we clearly observed thicker spallated layers which can be removed easily. Therefore, sapllation is considered as dominant mechanism for all samples of group II. However, according to our observations, although outer surface of all wet samples shows a small amount of melted materials, but, we think spallation is the main mechanism of laser perforation for wet concrete. Table 2 represents results of our experiments related to group II. According to Table 2 changes in diameter of holes for group II were negligible for all exposure times. Vice versa, there was a significant growth in the diameters for group I with illumination time (Fig. 3). Since beam diameter was about 4 mm, therefore, it seems use of water during the laser illumination leads to a more exact perforation of concrete.

Moreover, based on Tables 1 and 2, the ratio of depths (wet to dry) for 2, 6, 15, 30 and 60 s was calculated 10, 8.75, 5.71, 4.67 and 3.6, respectively. Specially, illumination of wet concrete during 2 s showed 4 mm perforation depth which was 10 times greater than that of dry sample (Fig. 4), but, at 60 s exposure time the ratio reduced to 3.6. Therefore, presence of water had positive effect on

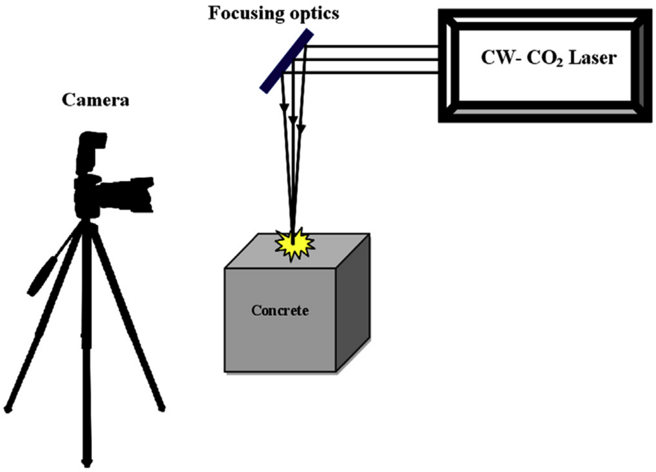

Fig. 1. Schematic of experimental set up for laser perforation study.