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Specific Energy for Laser Removal of Rocks

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Abstract

Application of advanced high power laser technology into oil and gas well drilling has been attracting significant research interests recently among research institutes, petroleum industries, and universities. Potential laser or laser-aided oil and gas well drilling has many advantages over the conventional rotary drilling, such as high penetration rate, reduction or elimination of tripping, casing, and bit costs, and enhanced well control, perforating and side-tracking capabilities.

The energy required to remove a unit volume of rock, namely the specific energy (SE), is a critical rock property data that can be used to determine both the technical and economic feasibility of laser oil and gas well drilling. When a high power laser beam is applied on a rock, it can remove the rock by thermal-spallation, melting or vaporization depending on the applied laser energy and the way the energy is applied. The most efficient rock removal mechanism would be the one that requires the minimum energy to remove a unit volume of rock. First, studies were carried out to investigate the correlation between the rock removal mechanisms and laser processing parameters. Then the test matrixes were carefully designed and performed based on the established correlation to quantitatively determine the nearly true specific energy. A 1.6 kW pulsed Nd:YAG laser, with a unique control capacity over laser parameters, is utilized to perform beam application tests on the rocks. The effect of laser processing parameters, such as beam irradiance, energy per pulse, exposure time, and pulse repetition rate, on the removal of rocks are investigated. The study found that different laser-rock interaction zones from intense melting to scorching could be produced in the rock depending on the applied beam irradiance and exposure time. However, the most efficient rock removal mechanism was found to be thermal-spallation where the rock was thermally fractured and removed from the hole before any further melting or vaporizing (which requires much higher energy). The study also found that increasing beam repetition rate within the same material removal mechanism would increase the material removal rate due to an increase of maximum temperature, thermal cycling frequency, and intensity of laser-driven shock wave within the rock.

Introduction

Since the turn of the twentieth century, rotary drilling has been a dominant technique for well production in the oil and gas industry. According to a Gas Technology Institute (GTI) study conducted in 1995, 50% of the well production time is spent on making hole, 25% of the time on tripping, and 25% of the time on casing/cementing. In 1999, approximately 20,000 wells, with an average depth of 6,000 feet, were drilled onshore in the U.S[1].. The total estimated cost, at rate of $128 per foot, was 15.36 billion. Major reduction in drilling costs can be obtained by drilling faster and reducing requirements for drill string removal, bit replacement and setting casing. Tremendous advances in high power laser technologies in recent decades showed the potential that laser can just do that. In fact, the initial laser drilling experiments on reservoir rocks conducted with the U.S. Army's Mid-Infrared Advanced Chemical Laser (MIRACLE) and the U.S. Air Force's Chemical Oxygen-Iodine Laser (COIL) systems showed the potential of laser drilling[2]. Both systems operated in the infrared optical region with power delivery capacities of 1 MW and 10 kW, respectively. The penetration rate by the systems was reported 100 times faster than current rates. Also, the experiments indicated that at such high powers there were deleterious secondary effects that increased as the hole depth increased. These effects included the melting and remelting of broken material, exsolving gas in the lased hole, and induced fractures, all of which reduced the energy transfer to the rock and therefore the penetration rate. More basic researches need to be done in a systematic scientific approach to better understand laser-rock interaction.

The energy required to remove a unit volume of rock, namely the specific energy (SE), is a critical rock property data that can be used to determine both the technical and economic feasibility of laser oil and gas well drilling. When a high power laser beam is applied on a rock, it can remove the rock by thermal-spallation, melting or vaporization depending on the applied laser energy and the way the energy is applied. The most efficient rock removal mechanism would be the one that requires the minimum energy to remove a unit volume of rock. Obtaining the true specific energy of laser drilling was very difficult due to the secondary effects caused mainly by the deep hole. In the current investigation, shallow holes were produced by carefully controlling the laser beam irradiance and exposure time in order to avoid most of the secondary effects. First, studies were carried out to investigate the correlation between the rock removal mechanisms and beam irradiance through a linear track method with simultaneous change of beam size on the rock surface. Then the test matrixes were carefully designed and performed based on the established correlation to quantitatively determine the nearly-true specific energy. A 6 kW CO_2 laser and a 1.6 kW pulsed Nd:YAG laser were utilized to perform beam application tests on three reservoir rocks: Berea Grey Sandstone, Frontier Shale, and Ratcliff Limestone. Only the SE results obtained using the Nd:YAG laser are reported in this paper. The effect of laser processing parameters, such as beam irradiance, energy per pulse, exposure time, and pulse repetition rate, on the removal of rocks are investigated. The study found that the most efficient rock removal mechanism was thermal-spallation where the rock was thermally fractured and debris were removed from the hole with the help of a coaxial purging gas before any further melting or vaporizing (which requires much higher energy). The study also found that increasing beam repetition rate within the same material removal mechanism zone would increase the material removal rate due to increase of maximum temperature, thermal cycling frequency, and intensity of laser-driven shock wave within the rock.

Experimental Procedures

Test materials

The rocks used in this study were Berea Grey Sandstone and Frontier Shale with two different dimensions: 1.27 cm in thickness and 7.62 cm in diameter disks and 25x5x1.8 cm slabs. Their composition and thermal properties are shown in Table 1[3].

Laser drilling system

The results reported here was conducted with a laser drilling system that consists of a 1.6 kW pulsed Nd:YAG laser with fiber-optic beam delivery, five-axis CNC workstation and coaxial purging gas unit (Figure 1). Fiber-optic beam delivery is

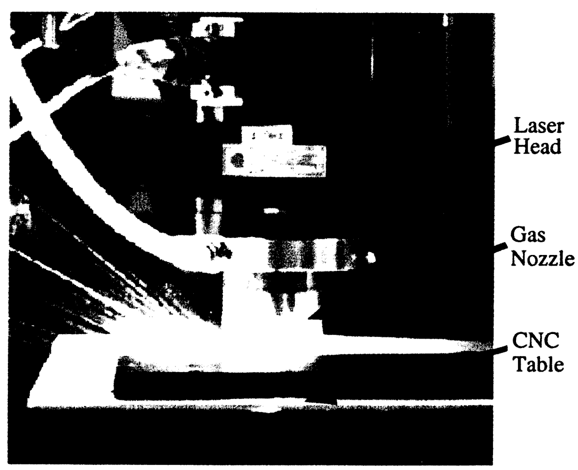


Figure 1. Annotated photograph of the laser drilling system.

particular attractive because of its inherent flexibility and potential to deliver the high power beam down in the well[4,5]. A 12.5-cm transmissive focusing lens producing a focused beam diameter of 985 μm was used. A constant nitrogen flow of 189 liter/min (400 ft^3/hour) was coaxially delivered to the rock by a drilling nozzle of 6 cm in diameter.

Table 1. Rock sample compositions and thermal properties

Rock type	Compositions	%	Bulk density (g/cm^3)	Thermal conductivity x 10^3 (cal/sec/cm^{0}C)	Heat capacity (cal/g^{0}C)	Diffusivity (cm^2/sec)
Berea Grey	SiO_2 Al_2O_3 Fe Rest	85 10 3 2	2.15	6.2	0.21	11.3
Shale	SiO_2 Al_2O_3 Fragment/clays	35 20 45	2.36	-	-	7.5

Linear track tests

In order to identify each possible laser-rock interaction zone and the corresponding laser processing parameters, a group of linear tracks were produced by continuously moving the slab under a beam whose focal position with respect to rock surface was simultaneously changed from -0.5 mm to 20 cm by moving the focussing lens upward away from the slab. Wide range of laser parameters were tested (Table 2). The ranges of parameters tested were energy per pulse from 2 to 32 J/pulse, repetition rate from 50 to 800 1/s, peak power from 4 to 16 kW, and pulse width from 0.5 to 2 ms. The calculated average power was fixed at 1600 W for each test, while the actual delivered (measured) powers were lower from 686 to 1310 W. The difference is mainly due to losses in the fiber optic delivery and the fact that at low energies/pulse (2 J/pulse) the laser does not output power as efficiently as at high energy per pulse.

Table 2. Laser parameters for Nd:YAG linear track tests

Rock type	Calculate			Measured		
	Average power (W)	Peak power (W)	Energy per pulse (J/pulse)	Average power (W)	Peak power (W)	Energy per pulse (J/pulse)
Berea Grey	1600	4000	2	686	1715	0.86
	1600	4000	4	874	2185	2.18
	1600	8000	8	1156	5780	5.78
	1600	8000	16	1236	6180	12.36
	1600	16,000	32	1310	13,000	26.2
Shale	1600	8000	16	1156	5780	5.78

Specific energy measurement

Based on the linear track results, test parameter matrixes around thermal spallation and slight melting zone, where the most potential minimum SE are, were selected and performed on disk rock samples. The matrixes included three energy per pulse levels (4, 8, and 16 J/pulse), each with specific pulse width and repetition rate. The pulse width was either 1 or 2 ms, whereas the repetition rate varied between 50 and 400 pulse/second. The beam diameters on the rock surface were 1.27 and 0.95 cm. The beam exposure time was controlled at 0.5 and 1.0 seconds to only produce a shallow hole so that the secondary effects could be avoided. To determine the material removed by the laser, the rock sample was precisely weighed pre and post lasing using a Mettler AT 261 balance with maximum 205g/62g and resolution 0.1mg/0.01mg. The removed volume was then calculated based on the rock bulk density.

Results And Discussion

Linear track tests

The resulting tracks are shown in Fig. 2. From left to right of the rock samples, different laser-rock interaction zones are identified by regions of similar physical reaction observed in the rock from intense melting to scorching. Also showing in the figure is the beam irradiance associated with each interaction zone, which decreased from left to right of the samples. For Berea Grey Sandstone, five zones identified are Zone I: significant melting/strongly-bonded glassy phase/deep narrow groove, Zone II: surface melting/cracked glassy layer/groove filled with glass and loose quarts underneath, Zone III: scattered surface melting/weakly-bonded material/trapped

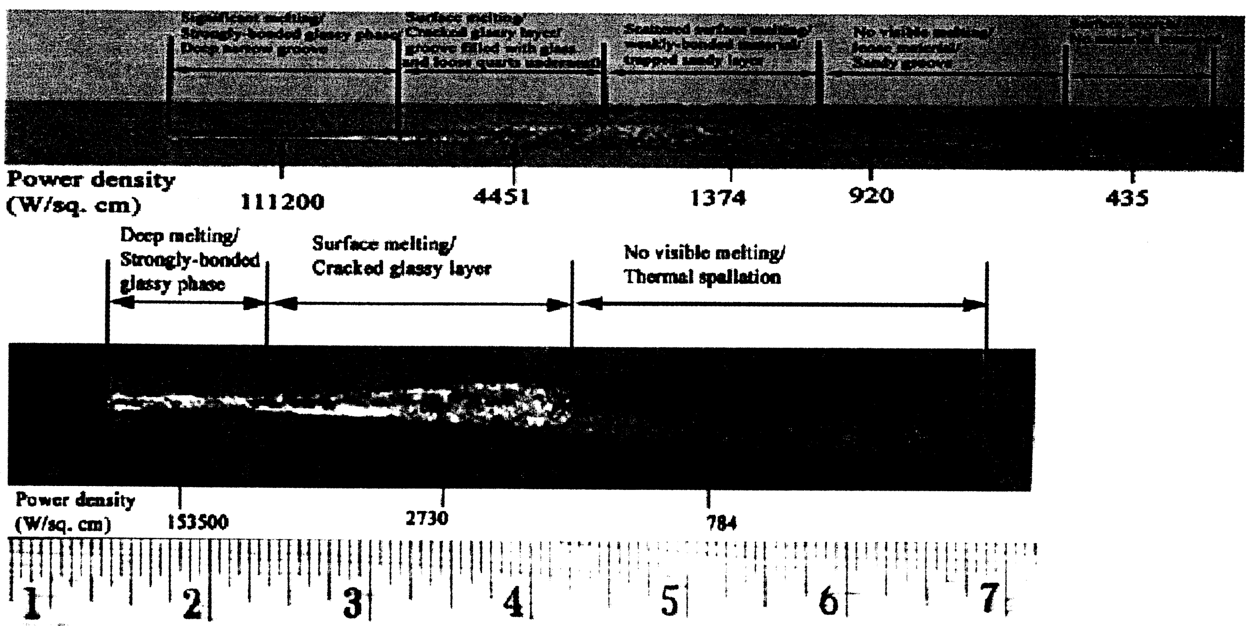


Figure 2. Nd:YAG linear tracks with focal position change of Berea Grey sandstone (up) and Shale (below) indicating the laser rock interaction zones and corresponding beam irradiance.

sandy layer, Zone IV: no visible melting/loose material/sandy groove and Zone V: surface scorch/no material removed. For Shale, only three interaction zones are identified. They are Zone I: deep melting/strongly-bond glassy phase, Zone II: surface melting/cracked glassy layer, and Zone III: no visible melting/thermal spallation. Though the actual amount of removed weight for each individual zone was not measured, visual observation of the linear tracks revealed that Zone IV for Berea Grey Sandstone and Zone III for Shale have the most efficient material removal mechanism. The corresponding laser beam irradiance for producing the thermal spallation zones are around 920 W/cm^2 for Berea Grey Sandstone and 784 W/cm2for Shale. The laser parameters for specific energy measurement test were selected from those two zones.

Specific energy measurement

Figure 3 shows the specific energy for Shale samples as a function of laser power under fixed beam spot size of 0.5 inches and exposure time of 0.5 seconds. The SE results were grouped together by thermal spalling and melting identified by the physical reaction observed on the rock samples (Figure 4). Thermal spalling produced a clear hole, and melting left melted deposits in the hole. AT very low power (200 W), the energy absorbed was only enough to heat up a small amount

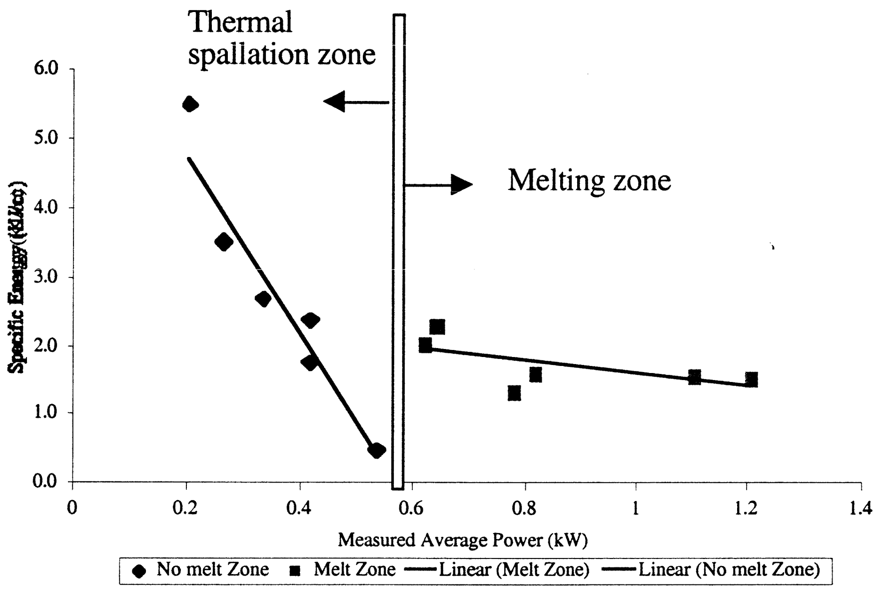


Figure 3. Specific energy as a function of laser power for Shale samples drilled at fixed beam size of 0.5 inches and exposure time of 0.5 seconds.

of rock and thermally fractured it; therefore, the SE is very high. As the power increased, a large volume of rock was heated up and fractured, resulting in small SE. This trend continues until the melting of rock started at power over 600 W. There is a sharp increase of SE (from 0.5 to 2.2 kJ/cm^3) when transition occurred from thermal spallation zone to melting zone. The SE decreased slightly in the melting zone as the laser power increased. This is due to the small reduction of the viscosity of the liquid phase at higher temperature [6] by higher power, and lighter liquid was easier removed from the hole by the purging gas.

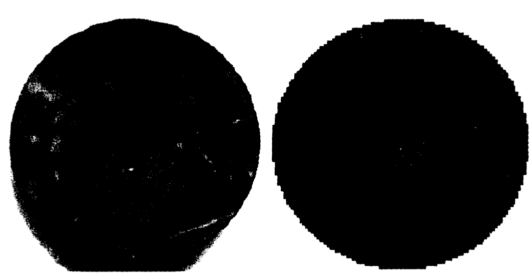
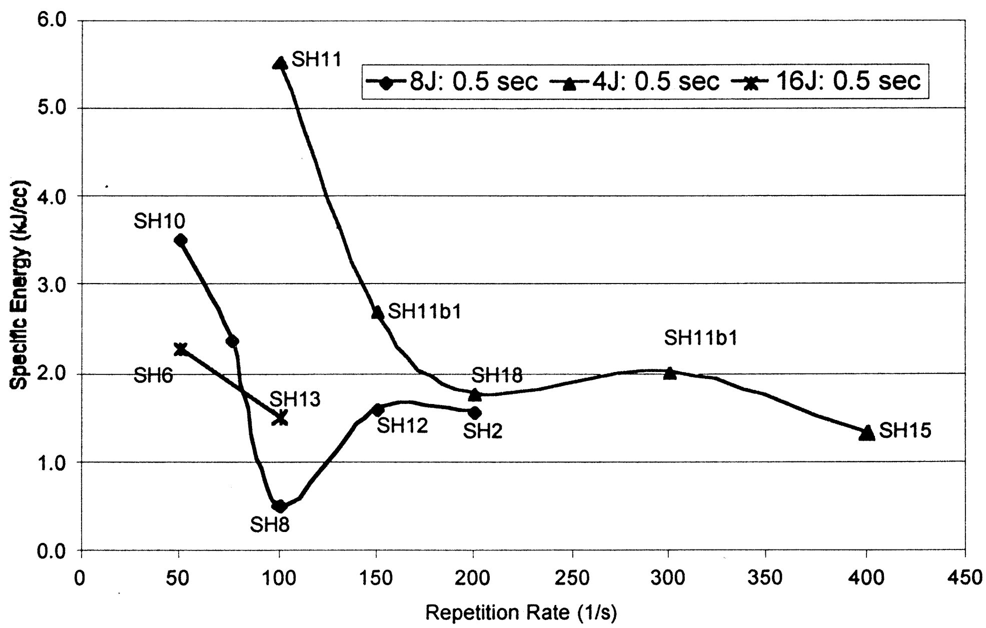


Figure 4. Photographs showing the laser-drilled clear hole by thermal spallation (left) and hole with melted deposits by melting (right).

The effects of repetition rate and energy per pulse on SE are shown in Figure 5. The group of 8 J/pulse has smallest SE. Too high energy per pulse, e.g. 16 J/pulse, the rock would be melted, therefore, increased the SE. Too low energy per pulse, 4 J/pulse, small volume of rock would be heated up and removed, leading to the same high SE. For constant energy per pulse, 8 or 4 J/pulse, increasing repetition rate reduced the SE first in thermal spallation zone, then increased the SE as the mechanism changed into melting. After melting started, the SE decreased slightly as repetition rate increased. As shown by the point SH13, SH2 and SH15 in Figure 5, it is very interesting to note that SE data produced at constant calculated laser power of 1.6 kW but high energy per pulse and low repetition rate (SH13, 16 J/pulse, 100 1/s), medium energy per pules and repetition rate (SH2, 8 J/pulse, 200 1/s), and low energy per pulse and high repetition rate (SH15, 4 J/pulse, 400 1/s), were about same. In other words, same penetration rate could be achieved by using different laser parameter combination. Two major factors that control the material removal rate are the maximum temperature (MT) and temperature cycling frequency (TCF) in the thermal spalling dominant zone. MT, largely controlled by the applied energy per pulse, determines the temperature difference (ΔT) in the rock, which in turn determines the thermal stress in the rock that is proportional to ΔT. When the thermal stress reached the static rupture strength of the rock, fracture of rock occurred. Fracture of rock could also occur at a stress that is lower than the rupture strength of the rock but cyclic from tension to compression. Increase of repetition rate of the laser beam would increase the cyclic frequency of the thermal stress and enhance the fracture. When overall effect of MT and TCF was constant, same SE results were expected. More systematic studies need to be done in the future to quantitatively characterize the laser-induced temperature and thermal stress field in the rock. Another contributor to the material removal is the laser-driven shock wave, which was detected by many researchers[7, 8] and also by the current study. Increasing repetition rate increased the intensity of the shock wave, therefore, reducing the specific energy.



Conclusions

1. Reservoir rocks can be removed by a high power laser beam through thermal spalling, melting, or vaporizing. However, thermal spallation is the most efficient rock removal mechanism that requires the smallest specific energy.
2. The laser beam irradiance required for producing the thermal spallation zones are around 920 W/cm^2 for Berea Grey Sandstone and 784 W/cm2for Shale.

3. The nearly-true specific energy for laser removal of rocks was obtained in this study by carefully controlling the laser beam irradiance and exposure time and avoiding most of the secondary effects.
4. As laser power increased, two rock removal zones, spallation and melting, were identified in the shale sample data with the least required SE occurring at the point prior to melting.
5. Increasing beam repetition rate within the same material removal mechanism zone would increase the material removal rate due to an increase of the maximum temperature, thermal cycling frequency, and intensity of laser-driven shock wave within the rock.

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