Laser Rock Drilling by A Super-Pulsed CO_2 Laser Beam

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Abstract

High power carbon dioxide lasers have successfully been used in drilling or cutting engineering materials such as metals, polymers and ceramics over the years. Can a carbon dioxide laser be used to efficiently drill different rocks in a deep gas well? Research sponsored by US Department of Energy has been carried out to answer this question. This paper will report the study results of using a super-pulsed CO_2 laser beam to drill rocks. A 6 kW CO_2 laser operated at superpulse mode was used to carry out the tests. Both linear tracks and deep holes were produced on the rocks. The energy required to remove a unit volume of rock, specific energy, was determined. Test results show that superpulsed CO_2 laser beam can be efficiently used to drill deep, large diameter holes in petroleum rocks with the assistance of purging gas.

Key words: CO_2 laser, rock drilling, specific energy

Introduction

Rock destruction and removal is a significant issue in the process of oil and gas development. Over the years, billions of cubic meter of rock have been removed with tremendous capital investment. In 1999, approximately 20,000 wells were drilled onshore in the United States, averaging about 1830 meters deep, at a cost of nearly $15 billion. This is equivalent to approximately 37,000 kilometers, or nearly three times the diameter of the Earth (12,756 meters).

Laser technology applied to drilling and completion operations has the potential to reduce drilling time, eliminate the necessity to remove and dispose of drilling cuttings and improve well performance through improved perforation operations. In 1997 the Gas Technology Institute initiated a two-year research program and successfully demonstrated the feasibility of using high power lasers for drilling and completing oil and natural gas wells [1]. Building on this, the U.S. Department of Energy funded the next phase to more fully investigate the basic scientific principles that can bring this laser drilling and completions concept within reach of an industry-supported prototype development. As a part of the basic scientific study, laser beam wavelength effect on rock removal has been studied. Two wavelengths studied are 10.6 μm from a 6 kW CO_2 laser and 1.06 μm from an 1.6 kW pulsed Nd:YAG laser. This paper will report the results from a 10.6 μm CO_2 beam interacting with petroleum rocks when it operates under superpulse operation mode. Comparison of the results obtained under continuous wave and superpulse operation mode is also presented.

Three operation modes of the CO_2 laser

The CO_2 laser used in the study can be operated under three different operation modes: continuous wave (CW), normal pulse (NP), and superpulsed pulse (SPP).

CW mode

When the laser is used in this mode, it continuously outputs a laser beam at the pre-selected power and beam transverse mode. A safety shutter at default close position directs the laser beam into a beam dumper when the laser beam is not used for processing. This hot-standby feature guarantees a stable and high quality beam can be delivered whenever it is needed. Controlling the shutter open time can control the sample exposure time to the laser radiation.

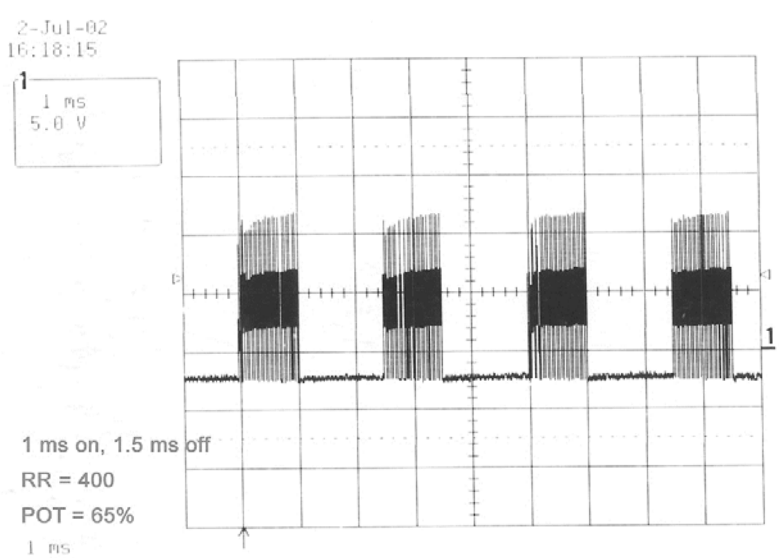

Figure 1 Waveforms of an electrically-pulsed CO_2 laser beam.

NP mode

The CO_2 laser can be also electrically pulsed under the condition that its peak power is equal to its CW average power, or a chopped CW beam. As shown in Figure 1, an equal portion of the CW beam is periodically chopped off. The beam transverse mode will be same as the mode used in CW mode.

SPP mode

Superpulse operation of the CO_2 laser typically generates 4 to 5 times the nominal optical power, for example24 kW for the 6 kW laser. The parameters subjected for superpulse are inherently limited by the radiofrequency (RF) excitation tube and gas discharge characteristics. For superpulse the RF tube can be subjected to 4 times the nominal electrical CW power, but only if the average power does not exceed the maximum CW power. Reliable superpulse operation is achieved if the 4 times enhancement is at 25% pulse duty cycle, for example, for 100 μs on time, the minimum off time is 300 μs. The relationship between average power ($P_{average}$) and pulse peak power (P_{peak}) is as follows:

$$P_{peak} = \frac{T(on) + T(off)}{T(0n)} \times P_{average}$$

Where T (on) = pulse on time
T (off) = pulse off time

A typical superpulsed pulse shape is shown in Fig. 2.

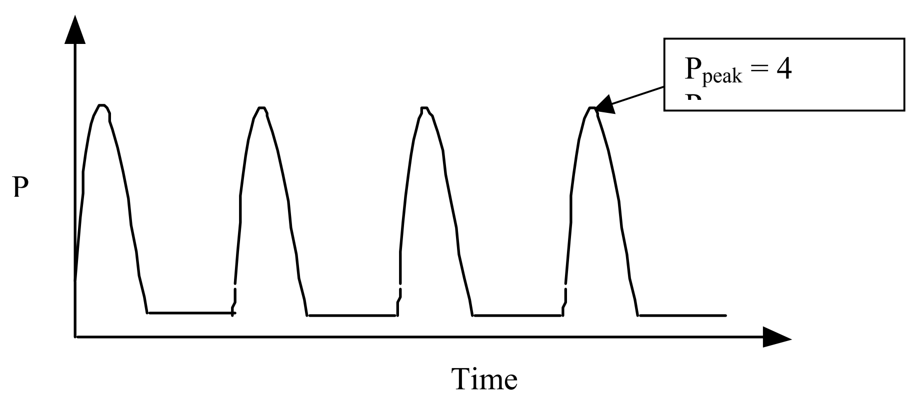

Figure 2. Schematic of typical superpulse pulse waveforms.

Experinmental precedures

The results reported here were conducted with a laser drilling system that consists of a 6 kW CO_2 laser, five-axis CNC workstation and purging gas unit (Figure 3). A 12.7-cm transmissive focusing lens was used. A constant nitrogen flow of 189 liter/min (400 ft^3/hour) was delivered to the rock by a purging gas unit. The most effective purging gas configuration of double side 60^0 shown in Fig.2 was used for the rock drilling tests. The

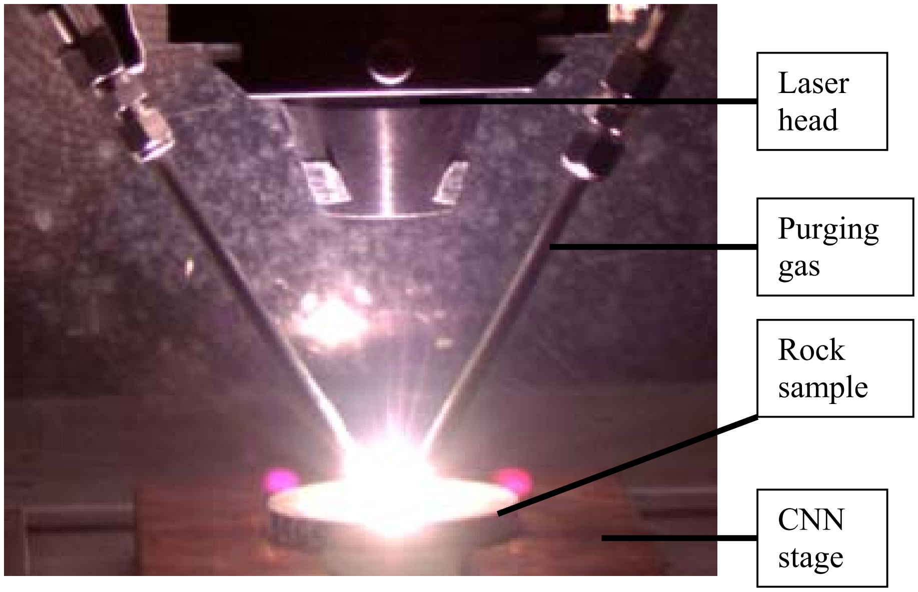

Figure 2 Photograph of the laser rock drilling system

tested reservoir rocks are Berea Grey sandstone and Ratcliff Limestone. Rock sample composition and thermal properties are listed in Table 1.

Table 1. Rock sample compositions and thermal properties

Rock type	Compositions	%	Bulk density (g/cm^3)	Thermal conductivity x 10^3 ($cal/sec/cm^0C$)	Heat capacity (cal/g^0C)	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
Limestone	$CaCo_3$ MgO Rock fragment	85 15 5	2.41	4.8	0.22	8.1

Linear tracks were produced by continuously moving the slab under a beam whose focal position with respect to rock surface was simultaneously changed by moving the focusing lens upward away from the slab. A coaxial purging gas of nitrogen at 189 liter per minute was applied by a coaxial nozzle that was attached to the focusing modular. The purging gas pressure on the rock sample was reduced while the nozzle was moved away with the focusing modular. A fixed purging gas delivering system was also tested. In this purging configuration, the distance between the nozzle and rock surface was fixed at 1 cm with the delivering tube/tubes placed at 60^0 from horizontal so that the constant gas pressure was delivered to the rock while the focusing modular moving away from the rock. Based on the linear track results, test parameters around the thermal spallation and slight melting zone, where the most potential minimum SE is, were selected and performed on disk rock samples. A defocused beam size of 6.3 mm in diameter was used to drill the holes for both operation modes. Gas purging configuration of two side 60^0 tubes, each with 10 cm from the rock surface and flow rate of 189 liter per minute, was used though other configurations were tested. The two symmetrical 60-degree purges produced the most promise results. 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 discussions

Comparison of linear tracks

Figure 4 shows two linear tracks produced by a CW CO_2 laser beam at 2530 watts power and travel speed of 190 cm/min with nitrogen purging gas of 189 liter/min moving away from the rock (Fig. 4, top) and fixing at 1 cm from the rock (Fig. 4, bottom). A

Figure 4. Comparison of linear tracks produced with changed (top) and fixed (bottom) purging gas position. Fixed gas nozzle helped to produce a clean track.

layer of glass phase remains on the track surface for changing purging gas position case, which is the indication of rock melting during lasing. When the purging gas nozzle was fixed at 1 cm from the rock surface, a strong pressure gas was delivered to the rock constantly. As a result, most of the melting deposits, shown in Figure 4, top, were removed from the rock surface before they solidified and deposited on the track surface.

Strong pressure from purging gas helped removing melting rock and improving the rock removal rate.

Figure 5 shows two tracks made under CW (Fig. 5, top) and SPP (Fig. 5, bottom) operation mode with same average power and purging gas fixed 1 cm from the surface. The appearances of the two tracks are almost identical, indicating the difference introduced by the two operation modes on rock removal is not significant and overridden by the gas purging effect.

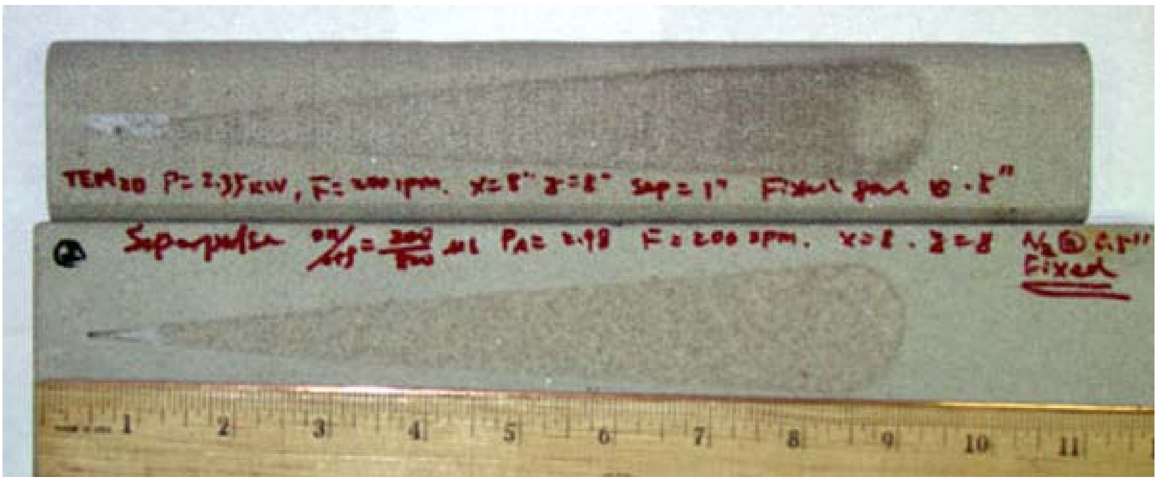

Figure 5. Comparison of linear tracks produced by CW beam (top) and superpulsed pulse beam (bottom) showing similar surface characteristics.

Comparison of drilling holes

Holes were drilled into limestone sample using CW and SPP beam. Gas purging configuration of two side 60^0 tubes, each with 10 cm from the rock surface and flow rate of 189 liter per minute, was used. Limestone was chosen as the test rock for deep hole drilling study because it was the only rock in which a through hole could be drilled without cracking the pieces. The superpulsed beam was pulsed at 200 μs on and 800 μs off, duty cycle of 20%, average power of 2800 W and peak power of 14 kW. The CW beam was run at average power of 2800 W and TEM_{20} mode. The top view and dimensions of the holes are shown in Fig. 6. The holes are slightly cone-shaped due to the divergence of the defocused beam over the hole depth. The specific energy as a function of the beam exposure time was determined and is shown in Fig. 7. Smaller specific energy (SE) was achieved for SPP beam over CW beam when the exposure time was short. But as the exposure time increased and the hole went deeper, the difference of SE for both operation modes becomes smaller and smaller. The short exposure time produced a shallow hole where deleterious secondary effects, such as the melting and remelting of broken material, exsolving gas in the lased hole, and induced fracture, are minimum. All of the secondary effects reduced the energy transfer to the rock and therefore the penetration rate. As the hole became deeper, the intensity of the secondary effects increased. As a result, the advantage of SPP over CW was gradually overridden. The minimum specific energy of 5.1 kJ/cm^3 was obtained by SPP beam at the shortest exposure time of 0.25 seconds, which corresponds a rate of penetration of 66 meter/hour. This SE value is about 2.5 times smaller than the minimum SE value obtained by lasing a pulsed Nd:YAG laser beam on the same limestone rocks [2]. But this is believed mainly

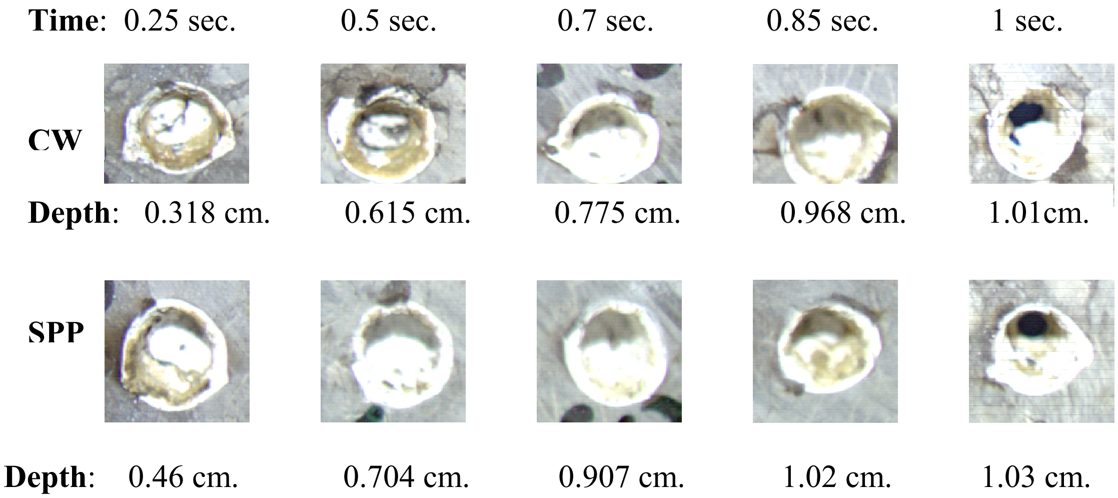

Figure 6. Top view of holes drilled with different beam exposure time and laser operation modes. The hole diameter is 6.3 mm.

due to much smaller hole diameter drilled in pulsed Nd:YAG case. A beam diameter of 3 mm was used in the pulsed Nd:YAG case, which is two times smaller than the SPP CO_2 beam size used. The intensity of the secondary effect dramatically decreased as the hole diameter increased.

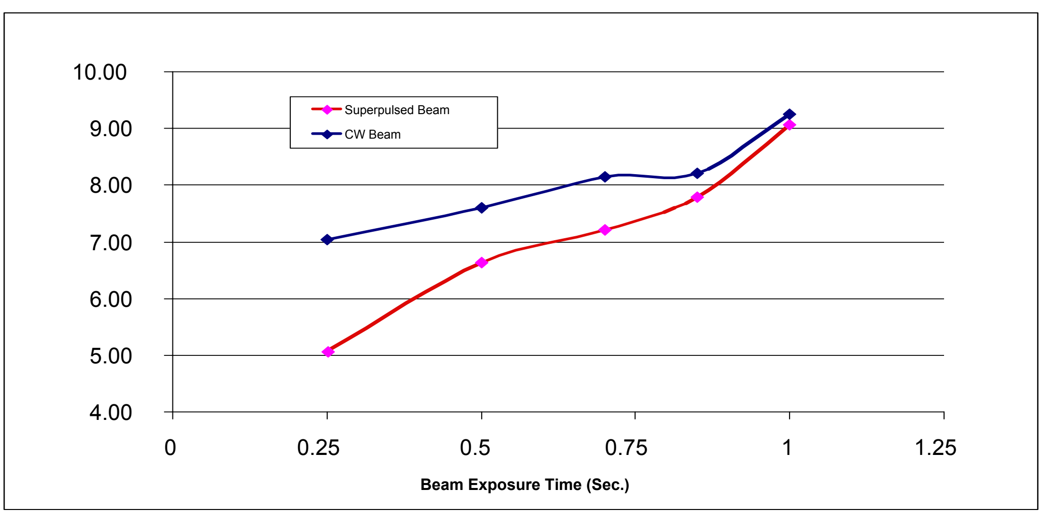

Figure 7 Comparison of specific energy as a function of beam exposure time for CW and SPP CO_2laser beam rock drilling.

Interaction mechanism of laser beam energy and limestone

Limestone is a general term embracing carbonate rocks or fossils. It is composed primarily of calcium carbonate or combinations of calcium and magnesium carbonate with varying amounts of impurities, the most common of which are silica and alumina. The two most fundamental types of limestone are high calcium and dolomitic. When laser energy is applied to the limestone, the following chemical reactions happen:

$$CaCO_3 \text{ (high calcium limestone)} + \text{heat} \Leftrightarrow CaO \text{ (h.c.quicklime)} + Co_2$$

$$CaCO_3 \bullet MgCO_3 \text{ (dolomitic limestone)} + \text{heat} \Leftrightarrow CaO \bullet MgO \text{ (dol. Quicklime)} + 2CO_2$$

There are three essential factors in the kinetics of limestone's decomposition.

1. The rock must be heated to the dissociation temperature of the carbonates. For calcite, the dissociation temperature is 898 ^{0}C (1648^{0}F) for 760 mm. Pressure (1 atm.) for a 100% CO_2 atmosphere [3,4]. The dissociation temperature of dolomite is 402 to 480 ^{0}C (756 to 896^{0}F)[5,6].
2. This minimum temperature must be maintained for a certain duration.
3. The carbon dioxide gas that is evolved must be removed.

The rate of dissociation is mainly controlled by the temperature. Mather[7] discovered that an increase in temperature of 50 ^{0}F exerted as much influence on the rate

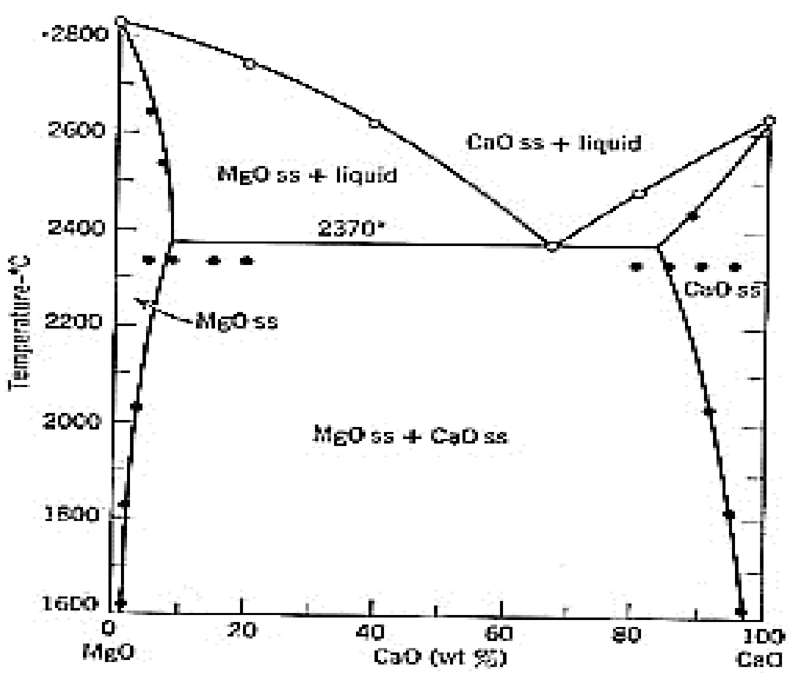

Figure 8 Phase equilibrium diagram for system CaO-MgO. Solid circles are data points of solid solution, and open circles represent liquidus points.

as extending burning time from two to ten hours. In the case of laser drilling, the temperature of local lased area could be 2 to 3 times higher than the dissociation temperature; therefore the rate may be extremely fast.

The melting point (MP) of CaO and MgO can be found from the phase equilibrium diagram for system CaO-MgO shown in Figure 8[8]. MP for 100% CaO is 2625 ^{0}C and 2825 ^{0}C for MgO. The boiling point for CaO is 2850 ^{0}C and 3600 ^{0}C for MgO. Some degree of melting did show on some of the laser-drilled holes (Figure 6), which indicates that the local temperature heated by laser reached over 2625 ^{0}C at least. Even boiling or vaporizing of CaO could happen under some laser firing conditions.

Conclusions

1. Linear track produced under changing purging gas position shows melting deposits remaining on the tracks, which were efficiently removed by using a closer and fixed gas purging system.
2. While drilling a deep hole in limestone, superpulsed pulse beam required a smaller specific energy than continuous wave beam did when the hole was still shallow. But as the hole went deeper, the difference of SE obtained by the two operation modes becomes smaller and smaller due to the increasing role of deleterious secondary effects.
3. The dominant laser material removal mechanism for limestone under current test conditions is combinations of decomposition and vaporization of Calcium Carbonate. The minimum SE for laser drilling of limestone under current test conditions is 5.1 kJ/cm^3.

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