Lasers May Offer Alternative to Conventional Wellbore Perforation Techniques

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Photonic technology shows promise in limiting formation damage and boosting production rates in oil and gas wellbore perforations.

For decades, well construction has developed into a process of varied steps designed to reach the hydrocarbon-bearing rock of the Earth's crust. In most cases, the final step in this process is to penetrate the tubular steel liners that hold reservoir fluids in place. Once completed, fluids are able to flow to the surface. Techniques introduced in the 1940s have remained the industry's primary method of wellbore perforation, using explosive charges to breech the steel and cement barrier. The explosive force of shaped charges, originally designed for anti-tank weapons in World War II, focuses a penetrating, small-diameter jet through casing and cement into the reservoir rock. Although an instantaneous process, significant damage can occur to the formation. Reservoir rock porosity and permeability are reduced as metal and cement debris are forced into the perforation tunnel, while very fine-grain particles plug or reduce the pore throats. In most cases, it is necessary to minimize flow restrictions into the wellbore through time-consuming and costly post-perforation operations.

For this reason, the Gas Technology Institute (GTI) has been looking at alternative perforation methods with high-energy lasers that reduce or eliminate formation damage, resulting in a significant boost in production rates, cumulative production and overall economic returns. GTI has repeatedly demonstrated through the application of high-power lasers to rock samples that permeability and porosity of the adjacent zones can be enhanced rather than damaged. By applying this technique downhole, perforations and other directionally controlled completion and stimulation methods could be employed without damaging the reservoir.

GTI is installing a 5-kW ytterbium fiber laser for use in its continuing research on the application of laser energy in well construction and completion.

Perforation history

Lined shaped charges were first developed and successfully applied as an anti-tank device in World War II. Soon after the war, this technology was transferred into the oil and gas industry for use as a cased hole perforation technique, remaining the standard in the industry. Unfortunately, this method can result in lower than optimal production – physical damage is created in the wall of the perforation tunnel and the adjacent formation zone.

Upon detonation, the explosive force of the shaped charge creates a high-velocity jet and extreme pressure aimed into the formation, ranging from 15 million psi at the tunnel entrance to 150,000psi at the penetration tip. As a result, the rock matrix is crushed and pore throats plugged or reduced in size from pulverized sand and cement particles, rock fragments, melted casing metal and explosive by-products (mostly carbon).

Attempts are generally made to remediate the damage created through perforation. During the years, a number of stimulation and other remediation techniques have been developed and applied to reduce the effects of flow restrictions. Although the effects of the wellbore damage may be reduced, they cannot be eliminated.

One approach GTI is investigating seeks to create a non-explosive alternative to shaped charge perforation using high-power lasers. Photonic energy can create fluid communication channels from the reservoir to the wellbore while enhancing the permeability and porosity in the tunnel and adjacent zones. Successful application could eliminate the production of debris, compaction of the rock formation adjacent to the tunnel, reduction in permeability, and health and safety concerns of explosives handling.

Laser/rock research

In 1997, GTI initiated a 2-year study to determine the feasibility of drilling and

Figure 1. The Berea sandstone block is shown after perforation using the MIRACL laser. After perforation, measurements of permeability and acoustic properties were taken.

completing oil and gas wells using high-power lasers developed by the U.S. military. Initial research in high-power laser/rock interaction sought to determine whether lasers have the required power, portability, reliability, durability, safety and environmental impact for economically drilling and completing oil and natural gas wells. The study showed that current laser technology is more than sufficient to break, melt or vaporize any lithology that may be encountered in the subsurface.

Lasers of various types, wavelengths and energy levels are used in many applications, including medical, manufacturing, material processing and the military. The principle of producing laser energy is to transform chemical, electrical or other forms of energy into a coherent, single wavelength of light. The wavelength of a laser (l) depends on the active medium employed, and can range from 0.1 micrometers (µm) to 103 µm, spanning the ultraviolet, visible, infrared and sub millimeter ranges of the photonic spectrum.

Two of the laser types used in this research were the mid-infrared advanced chemical laser (MIRACL) at the U.S. Army HELSTAF facility, White Sands, N.M.; and the chemical oxygen iodine laser (COIL) at the U.S Air Force Directed Energy facility in Albuquerque, N.M. The MIRACL and the COIL operate in the infrared region of the electromagnetic spectrum in continuous wavelength (CW) mode. The MIRACL has a power delivery capacity of 1.2 MW at 3.4 µm, and the COIL delivers at 15 kW at 1.34 µm. The size, type, shape, power and direction of each beam can be precisely controlled.

The MIRACL was used to perforate a dry block of 12-in. by 12-in. by 3-in. Berea sandstone in unstressed atmospheric conditions. Prior to the laser interaction, the average permeability of the block ranged from 2,500 md to 3,500 md, and the average porosity was measured at 23%. The maximum power of the CW beam was 900 kW, and the beam diameter was 2-in. The duration of the shots ranged from 4 sec to 6 sec and was made horizontally into the side of the rock to simulate a perforation orientation (Figure 1).

Several samples including Berea sandstone (BY and BG), reservoir sandstone (Sst), limestone (LS) and shale (SH) were lased using the COIL. Samples used for this test were cylindrical in shape, measuring 2-in. in diameter by 2-in. in length and 1-in. in diameter by 2-in. in length. The maximum power was 6 kW, the beam type was CW and the beam diameter was 0.25-in. The duration of the shots was 8 sec.

A series of analyses was performed to best characterize the rock samples before and after lasing, including mineralogy, rock properties, fracture identification, clay characterization and thermal analysis. The mineralogy of the samples before and after lasing was obtained from thin sections, X-ray diffraction (X-RD) and scanning electron microscope with energy depressive system (SEM-EDS). Changes in rock properties and phase of the rock depend on thermal conductivity, melting temperature, mineralogy and rock cementation. Thermal conductivity was documented from the literature. Melting temperature was measured by using the differential thermal analysis (DTA). Pre- and post-rock properties such as permeability, porosity and elastic moduli were measured, compared and quantified.

The permeability of each sample was determined in a way that depended on the shape and dimensions of the sample. Because of the large sample size of the Berea block lased by the MIRACL sandstone, a pressure-decay profile permeameter (PDPK-200) could be used to measure the point permeability before and after lasing. The measurements were taken at intersection points from a 1-in. spacing grid pattern mapped onto the rock. Once measured, the data was used to generate a contour map of post-lasing permeability (Figure 2). The PDPK-200 and data acquisition methodology was also used for the COIL samples. A core measurement system (CMS-300) was used to measure the permeability of the cylindrical cores prior to lasing but could not be used after the lased hole was created.

Zone analysis and perforation performance

One of the parameters used as an index to measure the perforation performance was core flow efficiency (CFE), where:

$$\mathrm{CFE} = \frac{k_p}{k_i} \qquad (1)$$

where k_p is the effective permeability of the penetrated zone and k_i is the ideal permeability of the undamaged zone (original formation permeability) in md. Equation 1 shows the strong correlation of the penetrated zone permeability on core flow efficiency and thus flow performance. If the value of CFE approximates 1, the zone is undamaged. If the penetrated zone is damaged, then the CFE will be reduced, affecting the flow and productivity of the well. How much CFE is less than 1 indicates the relative formation damage that has occurred. In most explosive perforation cases, CFE varies between 0.65 and 0.85. Case studies have shown average permeability reduction about 20%. The average thickness of the damaged zone is about 1.5 times the diameter of the perforation hole when shaped charges are used.

Several studies have been conducted to characterize and understand the damage caused by shaped charge perforation and its influence on productivity performance. Applying sufficient surge out of the formation or high production rates are common techniques used to remove the debris trapped in the tunnel; however, all debris may not be removed from the tunnel. Furthermore, the high flow rate may destabilize grains from the formation, causing sand production, and therefore has limited application. In addition to large debris left in the tunnel, very fine debris can get trapped in the tunnel because of its constricted geometric shape.

How much energy does it take?

Beginning in 2000, GTI and its research partners, Argonne National Laboratory, Colorado School of Mines and Parker Geoscience Consulting LLC, performed a series of experiments as part of an effort to more quantitatively determine the energy required for lasers to remove rock. As part of this investigation, the threshold parameters required to remove a maximum rock volume from the samples while minimizing energy input as measured by specific energy (SE, kilojoules/cubic centimeter) were identified. Samples of sandstone, limestone and shale were prepared for laser beam interaction using a 1.6-kW pulsed neodymium yttrium aluminum garnet (Nd:YAG) laser beam. Each sample was subjected to a single exposure of the beam to determine how the beam's size, power, repetition rate, pulse width, exposure time and energy can affect the amount of energy transferred to the rock for the purposes of spallation, melting and vaporization.

The study determined that using pulsed lasers could remove material from rock more efficiently than continuous wave lasers. The study also determined that reducing the effect of secondary energy-absorbing mechanisms resulted in lower energy requirements in shale and, to some extent, sandstones. These secondary mechanisms are defined as physical processes that divert beam energy from directly removing rock and may include thermally induced phase behavior changes of rock minerals (i.e., melting, vaporization and dissociation) and fractures created by thermal expansion. Limestone is spalled by a different mechanism and does not seem to be as affected by secondary mechanisms. It was also shown that the efficiency of the cutting mechanism improved by saturating porous rock samples with water, and that a laser beam injected directly through a water layer at a sandstone sample was able to spall and melt the sample.

Absorption of radiant energy from the laser beam gives rise to the thermal energy transfer required for the destruction and removal of the rock matrix. Results from the tests indicate each rock type has a set of optimal laser parameters to minimize specific energy (SE) values as observed in a set of linear track and spot tests. In addition, it was observed that the rates of heat diffusion in rocks are easily and quickly over-run by absorbed energy transfer rates from the laser beam to the rock. As absorbed energy outpaces heat diffusion by the rock matrix, local temperatures can rise to the melting points of the minerals and quickly increase observed SE values. The lowest values are obtained in the spalling zone (where rocks are broken into particles because of thermal energy) just prior to the onset of mineral melt.

Multiple burst experiments

In July 2002, a series of follow-up experiments were performed by the same research team to determine the effects of lasing multiple bursts into rock samples might have on specific energy calculations. One method of application for perforation was to place multiple beams of near-infrared energy adjacent to one another, collectively creating a hole, the size of which would depend on the number, arrangement and burst frequency of beams employed. The concept is similar to that of a mechanical drillbit in that individual tooth, buttons or cutters chip small pieces of rock as the bit turns under the weight of the drillstring. Since the rock experiences compressive failure under the concentrated load of each pressure point, the dimensions of the hole are a function of the number, arrangement and rate at which the points impact the rock under a given load. In both cases, a requisite amount of controlled energy is repeatedly delivered from the system to a point on the rock, causing it to fail in a predetermined path.

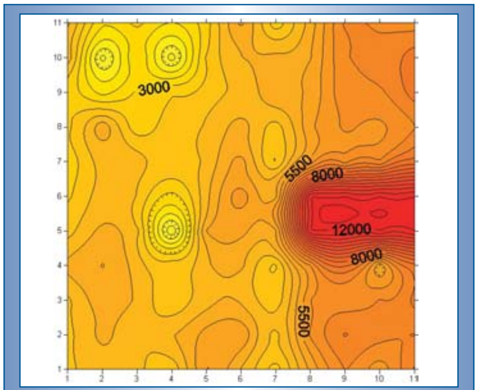

Figure 2. A contour map shows the permeability measurements of the Berea block sandstone, with permeability increases in the perforated tunnel.

The main goal of these experiments was to show that moving the beam interaction point on the rock sample in a geometric pattern can create a hole larger than the beam diameter and deeper than performed by single shots in the previous experiments.

Key considerations in designing the multiple burst test series included geometric pattern applications, beam overlap and spacing, focal distance changes while lasing, beam intercept angles, purging systems and thermal relaxation time between successive shots.

The same Nd:YAG pulsed laser was used in this experiment, where the same beam size,

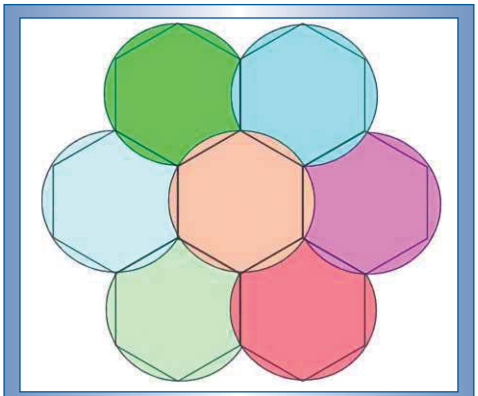

Figure 3. This diagram shows a hexagonal packing arrangement of laser bursts.

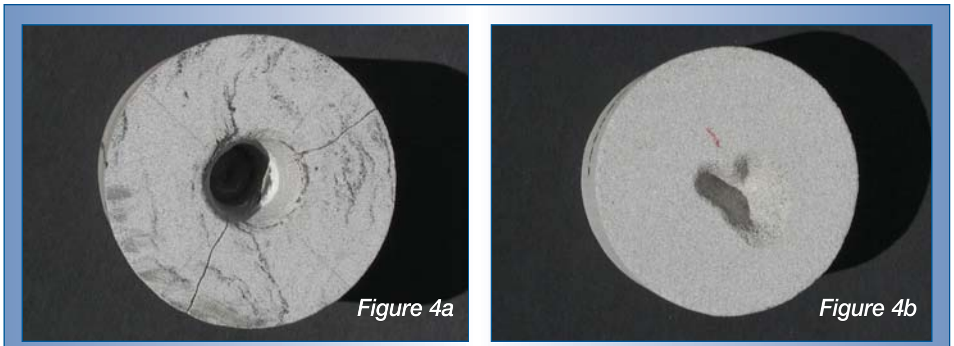

Figure 4a

Figure 4b

Figure 4. *The beam from a 6-kW carbon dioxide laser was applied for 8 sec to this cylindrical shale rock sample. It vaporized the rock to create a tunnel 1.8-in. deep and 1.06-in. in diameter. In figure 4b, this cylindrical sample of Berea gray sandstone (3-in. in diameter, 2-in. high) was subjected to multiple pulses in three different spots from a Nd:YAG laser. The beam diameter was 0.5 in. with a power density of about 1kW/sq cm. A total of 3.1 cc of material was removed by spallation.*

power, repetition rate, pulsed width, exposure time and energy could be precisely controlled. Those variables can affect the amount of energy transferred to the rock, along with any resulting material changes including spallation, melting and vaporization. In addition, select experiments were performed with a 6-kW carbon dioxide (CO_2) gas-type laser capable of continuous wave and super-pulsed beams.

Several geometries were contemplated for the multiple-hole tests. The pattern selected to give the best coverage, control of overlap and that which most closely approximated a circular outline is hexagonal closest packing (Figure 3). The spot size was set at 1.27 cm, providing a power density of about 1 kW/sq cm on the Nd:YAG laser and between 1.7 and 6 kW/sq cm on the CO_2 laser. The hole separation was varied to test beam overlap requirements to prevent any intermediary ridge from forming that would hinder downward movement of the matrix head as the hole was deepened.

For all tests, the laser parameters (pulse height, width and rate) were initially set to values previously determined to give the best SE per lithology. The first series of tests was to repeat application of laser energy on one spot with varying amounts of time between exposures. The second series was to create two spots next to each other, varying the spacing between the spots as well as the time between repeats. The third test series created three spots arranged in an equilateral triangle and four spots in a parallelogram. The four-spot tests were actually considered to be two equilateral triangles posted together.

The research team had access to one laser beam at a time. Therefore, moving the sample between shots on a five-axis mechanical stage created the multiple-spot locations. The stage was programmed to move the sample linearly back and forth for the two-spot tests and in triangular patterns for the three- and four-spot tests.

Test variables include the spot spacing, number of repeated passes over a given spot and relaxation time prior to repeating a shot. The spacing tests were performed primarily on the sandstone disks.

Results of multiple burst experiments

The results of the tests can be found in the Society of Petroleum Engineers Paper No. 84353. Overall, the SE behavior of the shale samples was similar to those observed in the sandstone. Observed SE values of the shales were generally higher than the previous single-spot, single-burst tests by almost an order of magnitude. The SE increased with increasing numbers of bursts even though melting was not much more evident in the higher burst number samples. The shale samples cut more easily than the limestone or sandstone, but SE values were significantly higher than the optimized single-shot, single-burst tests done in 2001. Some of the higher-count burst tests exhibited the highest SE values. The most likely reason is that the hole was getting deep enough that secondary effects, such as having exsolved gases absorbing the beam or particles released from the sample, were passing through the beam and absorbing energy.

In order to reach the threshold energy and power density for limestone on the Nd:YAG laser, the spot size must be reduced to the point that it quickly becomes a narrow hole instead of a shallow one, which means the secondary effects noted in previous narrow-hole work become significant. The liberated material cannot be scavenged and remains in the beam, parasitically absorbing energy. Likewise, exsolved gasses cannot be purged, and so they also absorb beam energy that would otherwise be used to spall the rock.

Using the higher average power available on the CO_2 laser allowed the hole size to be expanded to the experiment "standard" 1.27 cm while maintaining power densities high enough to get past the threshold. At all values, the SE calculated is significantly lower than tests done on the Nd:YAG, often by an order of magnitude. Based on the one-spot results on the Nd:YAG, it was decided not to attempt limestone multi-spot tests except on the CO_2 laser (Figure 4).

The results of this test series are encouraging in that the two- and three-spot tests indicate the weight loss levels off as number of bursts per shot increases. The two-shot tests indicate a precipitous increase in SE before the leveling occurs, but the three-shot tests indicate a very small increase in SE, which seems to be related to the relaxation time. The three-spot tests had relaxation times of 2.5 sec, the four-spot tests of 3.5 sec, while the two-spot tests had a maximum relaxation time of 1.5 sec.

The three- and four-spot tests were encouraging in that there was very little melting evident, even in the tests with 10 or 15 repeats on each spot (Figure 5).

Discussion

The sandstone and shale repeated-spot and multiple-spot tests indicate that SE increases with increasing numbers of repeats. The longer relaxation times resulting from the tests indicate rate of penetration may be limited by having to wait longer before illuminating the same spot again.

On the other hand, the tests revealed that limestone reacts well to the application of higher power densities as long as the spot size is kept large compared with the depth of the hole. The 1.6-kW Nd:YAG laser was not able to accomplish this. The power density available at the geometric test spot size was at or below the threshold levels necessary to cut the rock, so SE values skyrocketed. The CO_2 laser, with higher average power available, was able to increase power densities two to four times that of the Nd:YAG while keeping the geometric spot size.

The results from the range of average powers used on the CO_2 laser indicate that it would be worthwhile to do further tests with higher average power settings and power densities for all lithologies.

The multiple spot tests are supportive of the fiber-optic method of sending energy downhole. The geometric combination of many small spots will create a larger hole while avoiding the development of large amounts of energy-robbing melt. A previous independent study determined that fibers are capable of carrying power levels high enough to allow geometrically places spot sizes with power densities in the range necessary to quickly and efficiently cut rock.

Conclusions

It has been shown that high-power laser applications improved rock porosity and permeability in the perforated tunnel and in the adjacent zone. The changes in rock properties were related to thermal properties and mineralogy. Higher thermal conductivities resulted in better temperature distribution in the rock and, therefore, an increase in permeability and porosity. The results show there was an increase in permeability of up to 171% in sandstone and that improvement to permeability varied with the type of rock lased. The same has been observed in the porosity measurements.

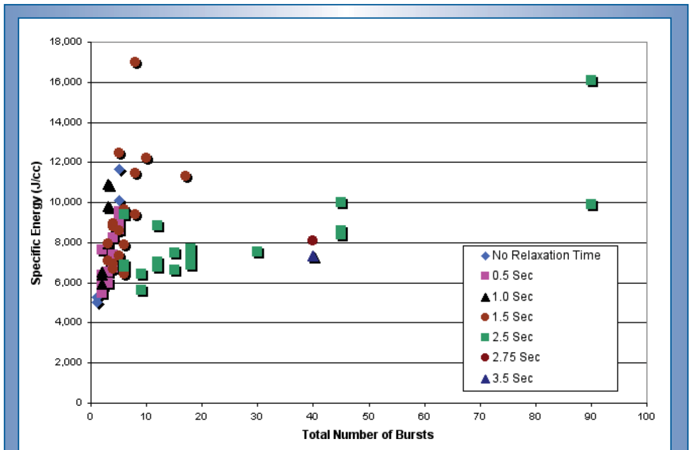

Figure 5. *All sandstone sample data (one-, two-, three- and four-spot) are shown, highlighting the major trend differences in observed SE values between 1.5 sec and 2.5 sec relaxation time between successive laser beam bursts.*

The results from perforating a block of sandstone using the MIRACL showed the laser produced a clean tunnel without debris and fine particles, primarily because of vaporization of material. There was no compacted or damaged zone around the perforated tunnel, and there were improvements to porosity and permeability in the adjacent zone. The tunnel size, shape, length and angle of the shot are highly controllable, and a well-defined hole can be created.

The results from the multiple-burst experiments likewise proved rock could be removed in a controlled fashion under spallation mechanisms and that a large hole can be created without the need for moving parts in the bottomhole assembly, such as a rastering or rotating system. The application of a significant amount of laser energy to a small rock sample without causing the onset of melting is very important – avoidance of melt is essential to efficient rock spalling.

The concept of the transport downhole of laser energy by means of fiber optics or other waveguide materials is supported by the low power requirements at each of the many spots to create a large hole in the subsurface. The power requirements are within the tested capabilities of current fiber-optics to significant depths, while technology in the research phase, such as hollow core fibers, may provide additional beam transport options in the future.

Results from both experiments continue to suggest the application of photonic energy may prove to offer a non-explosive alternative for perforating oil and gas wells. By applying this technique downhole through casing and cement, perforations and other directionally controlled completion and stimulation methods could be employed without creating damage to the reservoir. With the use of photonic energy, no perforating materials or explosive products are left to contaminate the wellbore and the perforation tunnel; therefore, cleaning the perforated tunnel and the wellbore around the perforation area are not required. In fact, the use of lasers in downhole completions techniques, including perforation, has the potential to stimulate the perforation tunnel while it is constructed. ✧

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