Fiber Laser Offers Fast Track to Clean Perforations

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Traditional methods of completing a cased hole include perforating with explosives, creating a tunnel to allow production of reservoir fluids to the surface. Although methods have been devised throughout the years to optimize this completion process, significant damage to the reservoir is typically created with a corresponding restriction to fluid flow. In addition to this damage are concerns of safety and security.

For the past 8 years, Gas Technology Institute (GTI) and its research partners have investigated the application of high-power laser energy for well construction and completion. Initial investigations were performed with larger military lasers to qualitatively demonstrate their feasibility for well construction. Additional work followed with less powerful, yet more practical and commercially available industrial lasers to determine rock-breaking energy requirements. In its most recent research, GTI advanced its downhole application research focusing on perforations using the most recent evolution of high-power lasers – a 5.34-kW ytterbium-doped multiclad fiber laser. The investigation has produced promising application results as well as an extensive testing of the most likely laser device to be deployed at a well site.

Early thoughts on laser applications

Since the earliest practical demonstration of lasers, the petroleum industry has recognized them as a potential alternative to, or means to assist, conventional mechanical methods of reaching and producing petroleum reserves. Many logical designs and methods were conceived and patented for subsurface laser applications that might offer revolutionary improvements in penetration rates and efficiency.

Laser technology, however, proved inadequate and impractical when first demonstrated. Lasers at the time were expensive and had limited practical applications, located primarily in academic and military settings. The lasers of the time had excessive power requirements, were large in size, and experienced poor reliability and frequent maintenance. Although technical progress and applications were expanding, limited energy transmission to subsurface targets and overall energy conversion inefficiencies tabled any real thoughts for applications in the petroleum industry.

By the late 1990s, laser technology had matured considerably when GTI and its partners investigated military and industrial lasers applications, only to dispel many of the oil and gas industry's previously held beliefs. With more technically advanced laser systems and the ability to better control beam application, it was shown that lasers were capable of breaking any lithology. Efficient rock removal methods of spallation and calcination were investigated, while avoiding more energy intensive methods of melting and vaporization.

Examination of post-lased rock properties yielded additional observations that supported laser application methods, particularly as part of a non-explosive perforations procedure. It was found that the transfer of thermal energy to the rock produced stimulation effects to fluid flow characteristics while rock was being removed. In Berea sandstone applications, porosity increased between 50% and 150%, and permeability increased 22% in the rock tunnel and surrounding areas. In addition, thermal energy weakened the overall strength of the rock in and around the excavated tunnel.

Key technical breakthrough in design

Historically, low-power versions of fiber lasers were used as optical signal amplifiers in the telecommunications industry. High-power configurations theoretically were achievable and only commercially realized in 2001. Since the design was scalable, fiber lasers were available with output powers nearing 10 kW within a year.

The principle behind the fiber laser is an internalization of the process that creates photonic emissions. In a fiber laser, photonic emissions are created in a doped silica "active" fiber using individually connected diodes, resulting in an efficient, compact laser source with exceptional beam quality. In other lasers, this process takes place in a separate resonance chamber energized by flash lamps or diodes. Laser emissions must then be channeled from the resonance chamber into an optical fiber or directly applied. Most industrial lasers are fiber connectable, although carbon dioxide (CO_2) laser emissions must be applied in a direct line of sight or through reflective optical tubes.

The unique design of the fiber laser allows a number of significant advantages over other industrial lasers. Together, these advantages have accelerated the practical application of high-power lasers for remote

applications, including well perforations and other well construction and completion methods. Notable improvements include: energy conversion, or wall plug efficiencies about 20%; the footprint of the 5.34-kW ytterbium fiber laser is 5.4 sq ft; and mean time to failure in excess of 50,000 hours of continuous operations.

The high wall plug efficiency of the fiber laser significantly reduces the required input energy compared with other industrial lasers generating the same output power. Assuming identical application conditions, a typical lamp-pumped Nd:YAG laser would require as much as 200 kW of electrical power compared with about 25 kW for an ytterbium fiber laser to send 4 kW of laser energy to a target (Figure 1). This represents 87.5% less input energy for the fiber laser to achieve the same output power. Less input energy results in a reduction of on-site electrical generation equipment and a reduction in cooling requirements for energy lost through thermal dissipation.

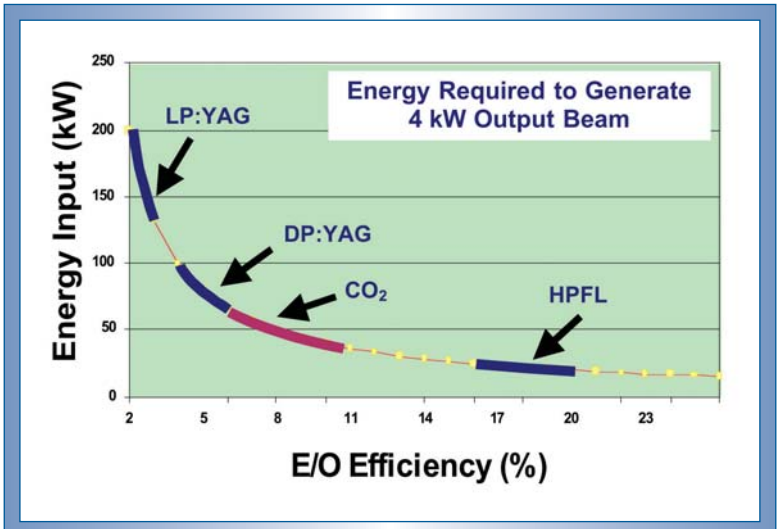

Figure 1. Comparison of required energy required of lamp-pumped Nd:YAG (LP:YAG), diode-pumped Nd:YAG (DP:YAG), carbon dioxide (CO_2) and high-power fiber laser (HPFL) to generate a 4-kW beam.

Perforating with fiber lasers

Given the advantages of fiber lasers over other high-power lasers, and the observed improvements they create in the fluid flow characteristics of rock, GTI performed a demonstration to further explore the practical application of fiber lasers for wellbore perforations.

Many of the previous experiments were performed using high-power lasers on Berea sandstone as it is well described in the literature as clean and relatively homogeneous in its physical properties with good fluid flow characteristics. Berea sandstone also has become the accepted standard for laboratory investigations of porous, permeable rock. A 1-ft cube of Berea sandstone was chosen to determine the ability of the fiber laser beam to tunnel through the block, the resulting energy requirement and resulting changes to rock properties. Since the influence of thermal energy on Berea previously was documented, we examined only permeability as an indicator of the extent of any changes in physical properties.

Previous laboratory experiments have observed laser/rock interactions of single or multiple beam bursts of several laser types on various lithologies with up to 4-in. x 6-in. length cylindrical core samples. The deepest penetrations recorded to date for a Berea sandstone was a 1-in. x 3¼-in. deep hole, created by a 6-kW CO_2 laser with a defocused, conical beam shape.

Specific energy (SE) was used to quantify the energy required to remove a unit amount of rock (kJ/cc). In previous experiments, optimal SE observations in Berea were determined using half-second beam exposures. The lowest recorded observations of SE in Berea under these controlled, optimized single shot conditions ranged from 4.3 kJ/cc to 5.2 kJ/cc. Later tests involving multiple shots were designed to layer single shots upon one another resulting in larger, deeper holes in Berea samples (about 1-in. in diameter and 1-in. deep) with SE values ranging from 9.2 kJ/cc to 13 kJ/cc.

The low values of SE were achieved by avoiding secondary effects, defined as processes that consume laser energy for purposes other than breaking the rock. Most of the secondary effects that occur in laser/rock interactions, including mineral melt, were avoided through limiting temperature accumulation in the exposed tunnel matrix and cuttings. As quartz is the dominate mineral in Berea (about 85%), melting occurs at temperatures greater than 2,700°F. Once mineral melt occurs, any additional energy the beam applies to the rock serves to increase the temperature of the melt rather than spallating the rock.

Altering the rate of energy transferred to the rock face while simultaneously reducing beam exposure to the cuttings as they exit the hole can control temperature accumulation in the rock. Energy transfer rates can be controlled easily through methods that include altering the average measured power applied, changing the power density (power/area) of the application or limiting the exposure time on a given area. Optimal beam power level and density were independently determined for fiber laser applications to Berea.

Cuttings removal is important in avoiding thermal accumulation. This becomes more apparent the deeper a hole is drilled. Experimental observations identified methods of creating a hole with a diameter larger than that of the applied beam. This was accomplished by moving the beam in a repetitive geometric pattern that allowed a

greater percentage of cuttings to exit the hole with limited or no exposure to the beam.

Tunneling through the target

The laser used for this demonstration was a 5.34-kW ytterbium-doped multiclad fiber laser with an emission wavelength of 1.07 microns (Figure 2), capable of generating continuous or pulsed beams. Although larger fiber lasers have been built, this is the largest available for research in the United States. Other major elements of the laser system included a tri-axial robotic arm mounted on a vibration free optical table, a gas purge nozzle, a fume extractor and beam dump. In addition, a beam collimator mounted on the robotic arm was used to convert the raw laser beam from the fiber into a collimated beam 1-in. in diameter. The robotic arm was programmed to move the beam in a circular motion 2-in. in diameter at 22.6 rpm.

A purge gas consisting of compressed air at 75 psig was directed through a stainless steel nozzle with a quarter-in. outlet diameter and maintained at about 1-in. from the target block by continuously moving it forward as the hole deepened.

The target block of Berea sandstone measuring 12-in. on each side was exposed to the beam for a total of 6 minutes. Permeability measurements were taken prior to beam exposure for later comparison to those taken after. Measurements were taken using a pressure-decay profile permeameter at intersections of a 1-in. grid system.

The beam was applied continuously at 1-minute intervals to avoid thermal accumulation. Laser power was maintained at an optimal level found in previous studies for this rock type (3.2 kW). When the beam penetrated half the length of the block, it was turned such that the beam could penetrate from the opposite direction and meet the existing tunnel in the block's center. This procedure was performed to reduce the influence of boundary effects and better simulate an infinite reservoir rock. Boundary effects had been observed as design artifacts of past experiments: as the beam approached rock sample edges, thermal diffusion characteristics are altered, regardless of the sample's physical dimensions.

Demonstration results

The resulting hole created in this demonstration passed through the full 12-in. length of the sample. The tunnel diameter was about 2-in. at the entry points on either face and 1.1-in. at the center of the block (Figure 3). Although a collimated beam was used and a uniform diameter hole was expected, the laser head assembly and purge nozzle were moved forward nonlinearly between laser applications.

An SE value for creating the entire tunnel was determined to be 5.5 kJ/cc. This represents one of the lowest values observed for a tunnel created by any laser source previously investigated. In addition, it was obtained while creating the deepest tunnel in Berea to date. This was achievable by limiting temperature accumulation and avoiding phase change of the rock minerals. Also notable in their contributions were the novel purging system that maximized ejection of cuttings from the hole and the applied circular motion of the beam that minimized cuttings exposure to the beam prior to ejection while limiting continuous beam exposure to the tunnel walls.

Comparisons of pre- and post-lased permeability measurements along the lased rock face perpendicular to the direction of the beam were inconclusive, as the deformation zone ext-

Figure 2. A 5.34-kW ytterbium-doped multiclad fiber laser with an emission wavelength of 1.07 microns.

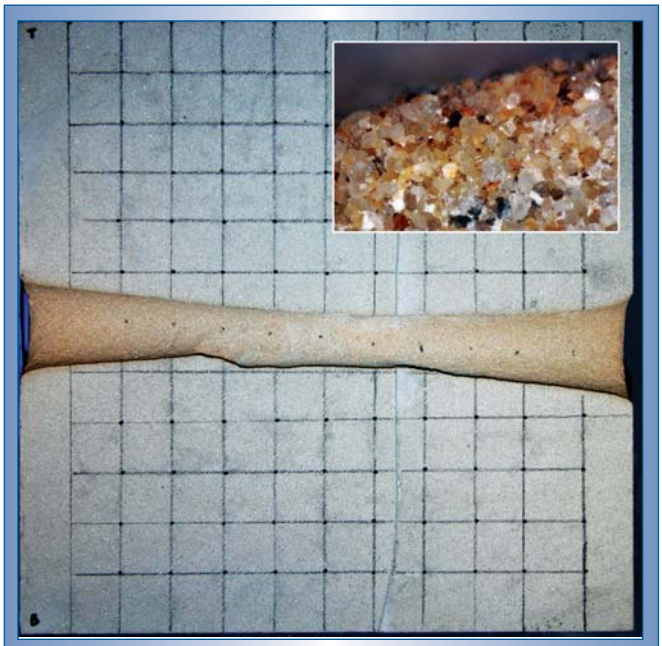

Figure 3. A cross-section of lased tunnel 12-in. across measuring 2-in. diameter on each end. The inset is a micrograph showing no evidence of melt and some discoloration.

ended only one-sixteenth-in. radially into the rock from the tunnel wall. This indicated, along with the observed SE value, that much of the energy directed at the sample was used to spallate the rock, and not to thermally alter near-tunnel rock properties. A similar comparison was made along the bisected length of the tunnel. There was no evidence of mineral melt on the tunnel wall. Post-lased permeability readings ranged from 100 mD (low) to 300 mD (high) with a pattern of highest permeability readings correlating with the tunnel. This represented permeability increases in the wellbore of between 15% and 30%. Although this enhancement is produced only within one-sixteenth-in. of the tunnel walls, we observed that the process of lasing perforation tunnels is at worst a non-damaging application (Figure 4).

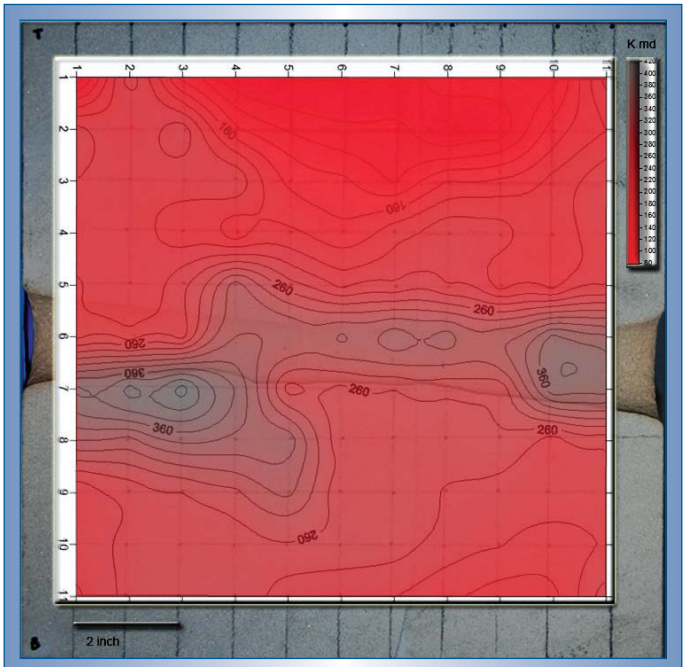

Figure 4. A two-dimension permeability map overlaying a photograph of tunnel cross-section.

Conclusions

The commercial introduction of high-power fiber lasers beginning in 2002 represented a significant step forward in realizing field-based applications of photonic energy for well construction and completion. Fiber lasers meet the multiple demands from industry regarding a field deployable system, including overall size limitations, mobile rugged on-site deployment, requisite energy delivery to target, real-time controllability and penetration of multiple materials.

From an economic perspective, the order of magnitude improvement in efficiency significantly lowers input energy and waste heat dissipation requirements. They also require minimal maintenance and repair, and are commercially available.

The application of GTI's 5.34-kW fiber laser to a 1-ft cubic block of Berea sandstone successfully demonstrated the most recent breakthrough in industrial laser technology. The demonstration provided a minimal value of SE when compared with previous laser/rock interaction tests, and yet was achieved while creating the deepest tunnel to date. This was made possible, in part, by effectively removing cuttings to avoid energy losses through thermal accumulations in the matrix and the cuttings. Additionally, boundary effects were minimized by using a target with a greater mass than found in cylindrical cores, and by opening the tunnel from both sides to meet in the center.

Evaluation of changes to rock properties proved that low power applications will create a narrower thermal deformation zone than megawatt military lasers. The deformation zone extends from the tunnel face radially into the rock; however the resulting impact on fluid flow enhancement is undetermined.

The importance of removing rock cuttings was again demonstrated, by means of creating tunnel diameters larger than beam diameters, and continually pushing gas purge lines into the deepening hole.

During the past 2 years, commercially available fiber lasers have increased in power from several watts to kilowatts. They are now capable of efficiently delivering requisite power via fiber optics to targets downhole, and have rapidly evolved into the leading candidate for on-site applications in well construction and completion. Their use as an alternative method to conventional explosive charges could reduce or eliminate perforation damage and significantly boost production rates, cumulative production and overall economic returns. ✧

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