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REVIEWS

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Laser drilling: reviewing the effect of purging system and formation parameters

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Abstract

Laser drilling is capable of reducing drilling costs and time. In laser drilling, a high rate of penetration (ROP) can be achieved, and the hole is cased due to laser interaction once it is drilled. In addition, laser technology can substitute conventional perforation techniques with no formation damage. Rock cutting with a laser beam is affected by various variables that fall within three categories; the rock parameters, purging system and experimental setup, and laser parameters. Each set of these categories affects the rock lasing process. Formation parameters include rock type, sample size, orientation, and the type of fluids saturating the rock sample. The purging system parameters include the type of purging system, application parameters, and the purging medium. Laser parameters involve laser type, laser application mode, beam power, duration, intensity, and frequency.

This paper reviews several experimental works performed by institutes, researchers, and entities to provide the reader with a comprehensive knowledge base for further experimental work, modeling for laser drilling, and studies. Because performed laser drilling experimental work is huge and covers tremendous aspects, only the purging system and effect of formation parameters were considered in this review, while laser parameters will be presented in a later paper. Results showed that the laser can drill swiftly through all rock types in conventional vertical, directional, or horizontal drilling. For optimum laser drilling, the purging system and its parameters must be carefully chosen, including the type of system, purging gas, gas pressure, distance to the lased sample surface, and the purging angle. The optimum purging system uses nitrogen as a purging fluid.

Keywords: Laser drilling, Laser directional drilling, Laser perforation, Specific energy, Effects of formation parameters on laser drilling, Porosity, Permeability enhancement by lasing

Introduction

Tremendous experimental investigations targeted the feasibility, application, and benefits of laser application for drilling and perforation operations of the petroleum industry and found that current industrial lasers are able to meet the needs of industry and achieve many benefits such as reducing costs, time, and environmental impacts [1–3]. Compared to conventional rotary drilling, lasers can achieve a higher rate of penetration (ROP) [4, 5] and drill the whole well in a single hole size with the advantage of creating tough, impermeable, ceramic sheath at well walls during drilling to act as the casing and cement (Fig. 1A) [1, 6, 7]. A rate of penetration (ROP) of 450 ft/h was recorded for laser application in drilling with the possibility of increasing ROP to more than 100 times of current rotary drilling recorded ROP values [1, 6]; this is much higher than what the dynamic underbalanced drilling (DUBD) technique can achieve [8]. Laser drilling also allows real-time communication and data gathering between the surface and bottom of the well which helps in decision-making and saves logging and formation evaluation costs [3, 9]. At the same time, the laser can increase recoverable reserves by making a portion of the resource economically profitable as a result of reduced drilling costs and enhancing the flow of reservoir fluids into the well

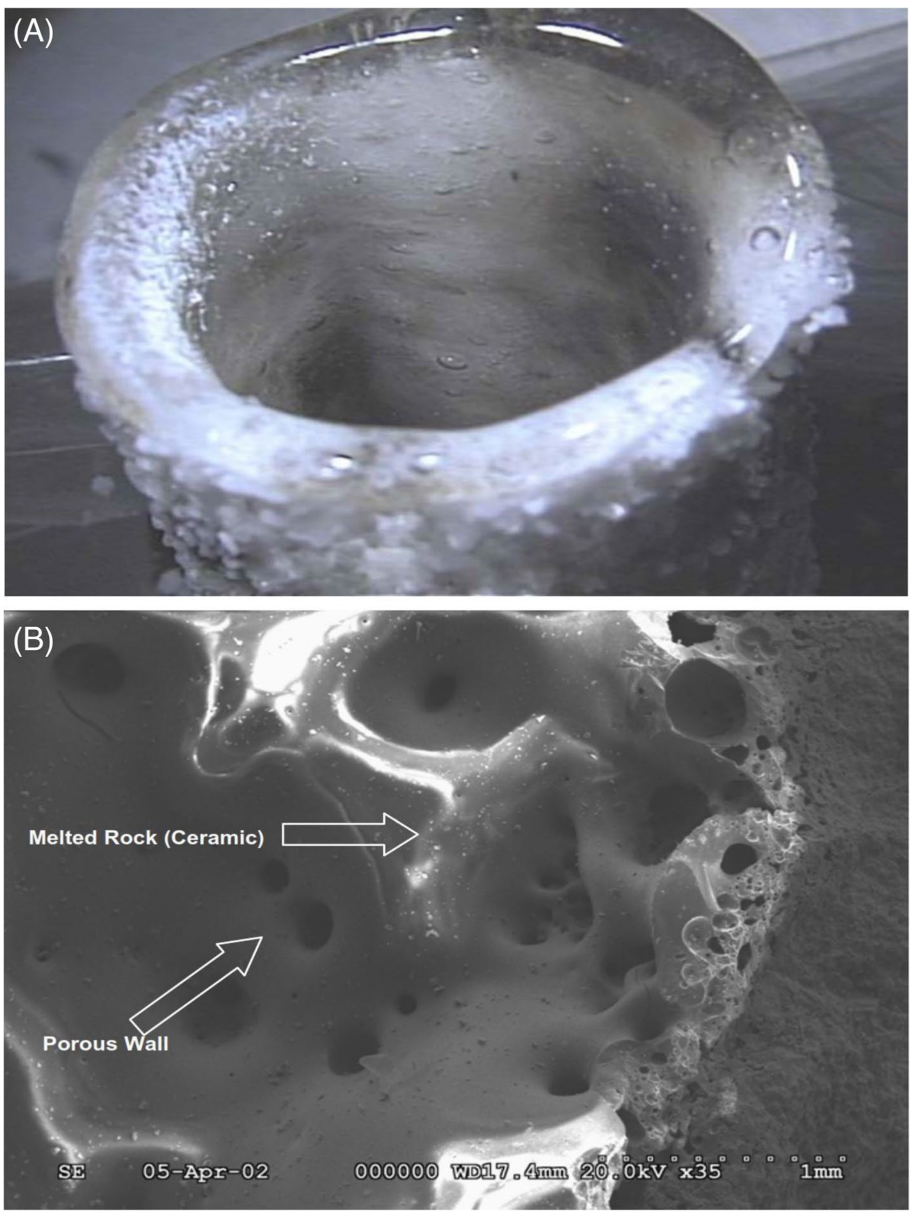

Fig. 1 **A** Impermeable tough wall melt. **B** Permeable tough wall melt created by COIL in Brea sandstone [6]

[3, 5]. High ROP achieved by laser drilling and the elimination of hazardous chemical additives of mud and cement make laser drilling cheaper and more friendly to the environment [1–3, 10]. Many published experimental works show the great benefits of using lasers as an alternative for perforation. A controlled shape of perforation with permeability and porosity enhancement due to micro-fractures and other thermal processes of the near perforated tunnels was recorded [3, 6, 11–14]. The laser can also be used for deep well perforation [15]. Extending the length of perforation tunnels increases effective communication to the reservoir formation [7]. For unconsolidated formations, laser perforation can provide a permeable consolidated perforation tunnel which can solve solid production problems (Fig. 1B). Moreover, laser perforation enables enhanced control during hydraulic fracturing [7]. These benefits and others can change some of the uneconomical resources into potential economic reserves, further increasing benefits.

There are two laser application methods for the drilling of oil and gas wells either using the laser to assist PDC bits (Fig. 2) or using the laser beam alone for the drilling and perforation. The first method is called the laser-assisted drill bits (or laser-mechanical drill bit) where a laser beam pattern is attached to the drill bit to weaken the rock before it is drilled (Fig. 2A–D). This method was applied in the oil field since 2009 by Frodo Energy Company. The mobile field system developed is shown in Fig. 2E. On the other hand, using laser alone for drilling oil wells in field application is not implemented up till now. The expected system components will be like the proposed system of laser-assisted drill bits.

The laser drilling system consists of the laser system which produces the laser beam and controls its properties and parameters such as frequency and power. The produced laser beam is then transferred to the bottom of the hole through fiber optics placed inside the coiled tubing system and is then further modified by the downhole optical system to control beam intensity, shape, and other properties. For example, the optical system may contain focusing lenses or a collimator. Beam intensity will depend on the beam shape, the separation between the focusing lens and the target, the focal length of the lens, and spot size. A nitrogen is a transparent, clear, and inert purging fluid. The purging system is utilized to clear cuttings. A drilling motor is utilized in the laser-assisted drill bits to provide the rotational motion of the bit. The hole is drilled till reaches the section depth, then the coiled tubing will be pulled out of the hole, and a casing string will be lowered. Laser perforation is then applied to perforate the well to establish communication with the reservoir.

The rock-cutting process is a complex operation that involves parameters falling into three categories: rock parameters, purging system/experimental setup, and laser parameters. Formation parameters involve lithology (rock type), boundary effect (sample size), sample orientation, fluid saturation, and others. The experimental setup and purging system have a great influence on laser interaction with rock. For example, if rock cuttings formed during laser drilling were not removed effectively away from the beam path, the beam will interact with the cut rock material instead of cutting a new rock part. Laser beam parameters involve beam application mode (continuous wave (CW) versus pulsed), beam power (peak power versus average power), lasing time (duration), beam intensity, pulse frequency and width, laser type, beam size, and shape, and spot shots or linear track application of the beam [2, 3, 9]. Experimental results show that the

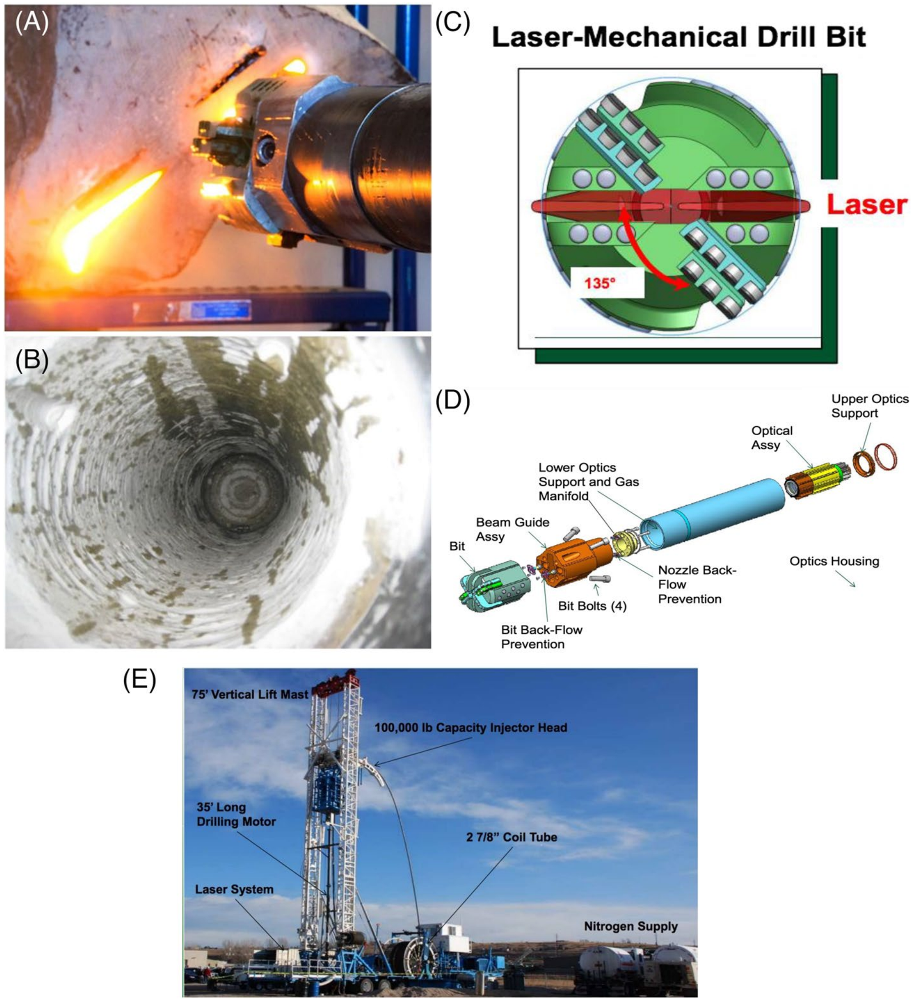

Fig. 2 Laser-assisted drill bit application. **A** Laser-assisted drill bit [16]. **B** 12 ft dolomite hole drilled with laser-assisted drill bit [16]. **C** Laser pattern and the PDC blades and cutters (https://www.nextbigfuture.com/2016/01/breakthroughs-in-high-power-fiber.html). **D** High-power laser drill head bit assembly (https://www.nextbigfuture.com/2016/01/breakthroughs-in-high-power-fiber.html). **E** Laser system for field application (https://www.nextbigfuture.com/2016/01/breakthroughs-in-high-power-fiber.html)

optimum rock lasing parameters to achieve the best drilling efficiency differ from one rock to another [2, 3]. There are several rock destruction mechanisms including mechanical stress, thermal spalling (Fig. 3A), fusion and vaporization (Fig. 3B), and chemical reactions [2, 3, 17–19]. All these mechanisms are achievable during laser drilling, and a good understanding of each mechanism together with the application targets enables achieving optimum laser drilling performance and efficiency. Tremendous experimental investigation works were performed to evaluate and test various aspects of laser drilling such as the applicability of laser drilling [1–3, 9], optimum parameters for drilling [2, 20–22], and perforation [5, 23–27], physical and chemical changes in rock [28], changes in rock properties and mineralogy [2, 11, 25, 29, 30], and other aspects.

The laser beam heats the rock at lasing point, which increases local temperature causing many changes such as thermal expansion, phase changes, chemical reactions, clays

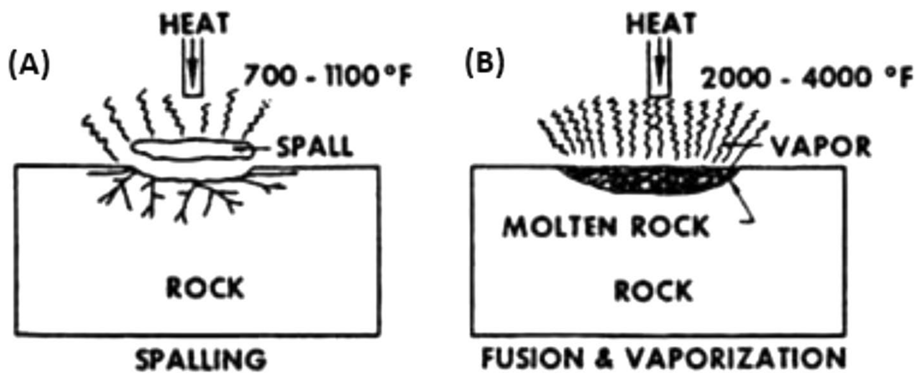

Fig. 3 Spalling, melting, and vaporization mechanisms of laser drilling [31]

dehydration, gas releasing, thermal stresses, and thermal dissociation of some components depending on temperature, heat dissipation to surroundings, rock mineralogy, purging system, and others [2, 3, 17, 18]. Because the thermal expansion of the lased rock zone is restrained by the surrounding rock matrix, mechanical stresses are developed through the rock causing rock failure. Thermal spallation (Fig. 3A) occurs at a low temperature, 400 °C–800 °C in sandstone [2, 32–36]. Adding more thermal energy results in a phase change to rock: melting and fusion (Fig. 3B) [2, 6, 17, 18, 32, 37]. Melting can be used to strengthen borehole wall aright after laser drilling which may eliminate the need to run casing [2, 3, 6]. Rocks typically have low thermal conductivity; therefore, rapid heating typically occurs in the vicinity of the lasing point. The heat generated at lasing point and in its vicinity can cause the dehydration of clays. Collapse of some clay minerals may also occur. For example, smectite collapses at 550 °C (Fig. 4) [3, 19, 38]. Heat dissipation is mainly controlled by rock mineralogy and grain packing. Some minerals are thermally decomposed when subjected to laser and consequently consume the beam energy. Closer grain packing facilitates heat dissipation and in consequence, reduces the temperature of the lased point [1, 2, 17, 18, 32].

When external mechanical (or thermal) stress is applied to a rock sample, induced mechanical (or thermal) stresses are developed that will increase as the externally applied stress is increased until it reaches a threshold value, where the resulting induced stresses overcome rock strength (or melting point). Beyond such threshold value failure (or melting) will initiate which is characterized by a constant energy level during the destruction process [2, 3]. Specific energy (SE) is a term introduced to evaluate the efficiency of various drilling methods where a higher SE value indicates lower drilling efficiency and vice versa [2, 3, 39–49]. SE is used to compare and evaluate the effect of each parameter on the efficiency of laser drilling. SE is defined as the amount of energy consumed to remove a unit volume of rock and is mathematically expressed as in Eq. 1 [2, 3, 39–46, 49, 50]:

$$SE = \frac{Energy\ consumed}{volume\ of\ removed\ rock} \tag{1}$$

In experimental laser drilling, energy consumed is the product of beam power and lasing duration. The volume of removed rock can be determined by one of two methods: the geometrical method or the weight difference method. In the geometrical method,

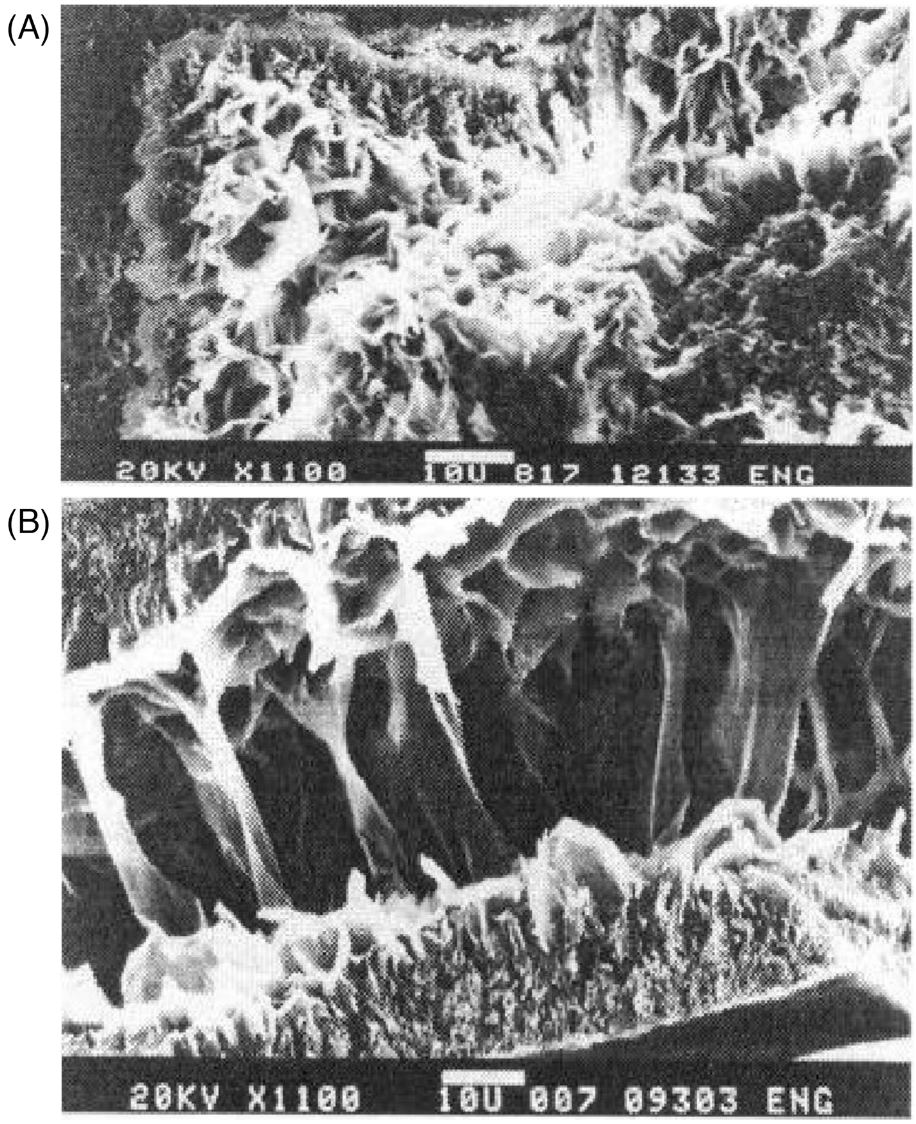

Fig. 4 Smectite dehydration and collapse with lasing. **A** Pre-lasing and **B** post-lasing structure [3, 27]

the created hole depth is measured and the volume is then calculated according to the beam shape, assuming the created hole is identical to the beam shape. The weight difference method calculates the volume of removed rock by multiplying the difference in sample weight before and after lasing by the average sample density. The geometrical method expresses the ideal drilling performance without melting while the weight difference method expresses the actual value of SE. In case no melting occurs, the two calculated SE values are almost identical. Generally, melting reduces drilling efficiency because a portion of laser energy is consumed in phase change (melting) rather than in rock cutting [2, 34, 51]; the molten material formed also reflects a portion of the incident beam away from the lasing point.

Effects of the purging system and rock parameters on the laser drilling process

Purging system and laser drilling optimization

Rock cuttings must be removed away as soon as they are detached to clear the beam path to cut a new rock material. If kept in place, cuttings in the beam path consume beam energy, leading to a substantial reduction in drilling efficiency and an increase in SE [19]. Two purging systems (the air amplifier and the gas nozzle purging systems [2]) were evaluated (Fig. 5). The air amplifier system uses compressed air feed to induce flow through the device from a suction inlet to output and can operate in both discharge and

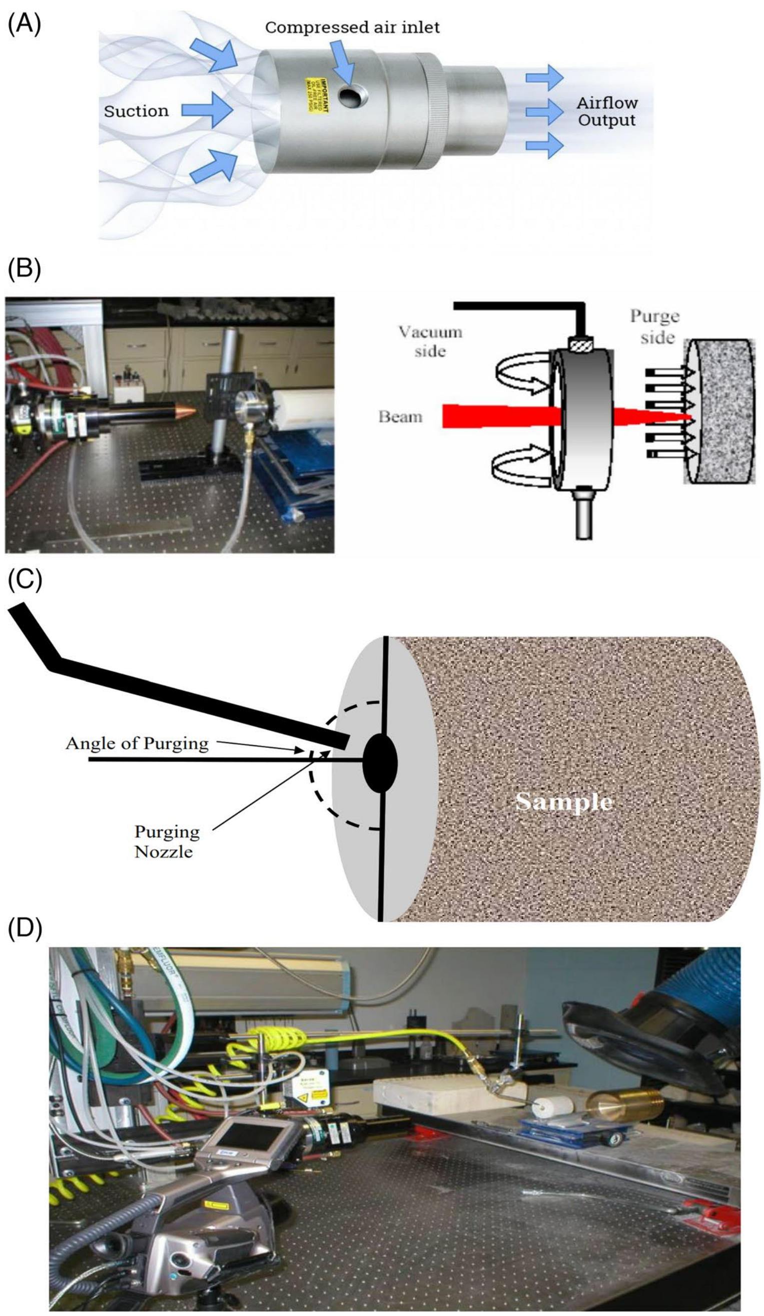

Fig. 5 **A** Air amplifier. **B** Air amplifier setup. **C** Gas nozzle purging. **E** Gas nozzle setup [2]

vacuum modes to provide uniform gas flow. In the gas nozzle purging system focused compressed gas is ejected through a certain nozzle size at an angle and specific separation distance from the rock surface. Both systems were investigated using samples of sandstone and limestone, where the SE for each lasing shot was calculated (using both volumetric and weight differential methods) for system evaluation.

Both systems showed a similar effect on limestone's SE. However, the SE for sandstone was generally lower with the gas nozzle system indicating a better efficiency (Fig. 6) [2]. The gas nozzle system gives a high-coaxial gas flow that removes silica effectively and prevents melting, which reduces SE. Therefore, the gas nozzle purging system was selected and tested for the optimum purging parameters by a set of experiments to determine the optimum gas pressure, nozzle size, the purging nozzle-sample separating distance, and purging angle [2]. Each parameter was tested while keeping the other parameters constant and measuring the SE value for each case. The optimum parameters are as follow: gas pressure 75 psig (≈90 psi), nozzle size 0.25 in., the separation between the nozzle and sample 1.0 in., and purging angle 35° [2].

The Gas Technology Institute (GTI) evaluated the effect of air, nitrogen, argon, and helium purging gases on the SE of laser drilling on cores of sandstone and limestone with 2.0 in. diameter and 2.0 in. length placed in a plexiglass chamber to contain samples in downhole simulated conditions during lasing. Each shot was repeated three times, and the SE was then averaged. Utilized laser beam was a 1.0 in. collimated, CW high-power fiber laser (HPFL) beam of 5.34 Kw power which was focused by a lens with 39.37 in. focal length to create a laser spot size of 0.35 in. on the sample face for 8.0 s. Of the various tested gases, nitrogen as a purging gas achieved the lowest SE value for limestone and very low SE for sandstone (Fig. 7). Figure 8 demonstrates the little variation of SE values for nitrogen and argon as purging gases for another COIL laser experimental investigation, where nitrogen provides a slightly lower SE value and is a cheaper choice compared to argon, for a dry Brea grey SS lased by COIL type laser for 8 s. Purging gas pressure was in the range of 10–15 psi [52].

Investigation of liquid purging fluids (such as water, optical fluid, and anti-freeze) was performed to determine their impacts on the sample lasing process [32]. Sandstone and

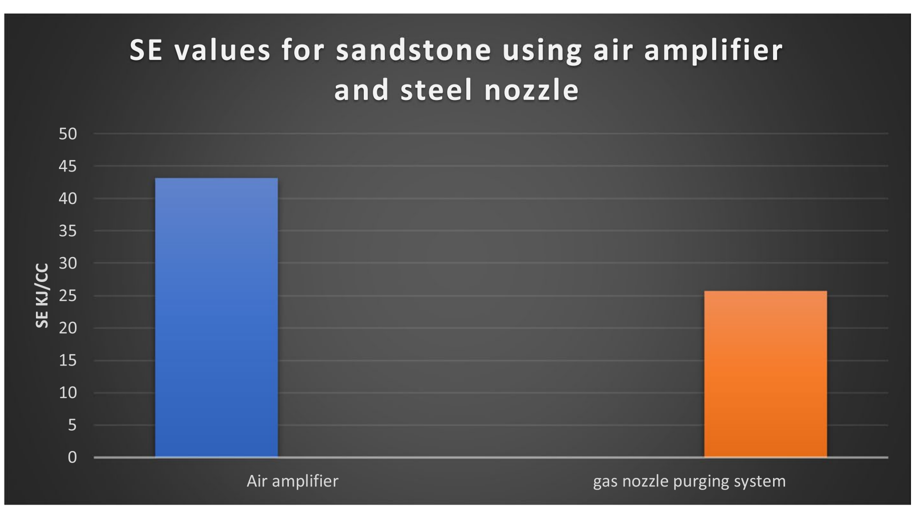

Fig. 6 SE values for sandstone with gas nozzle and air amplifier [2]

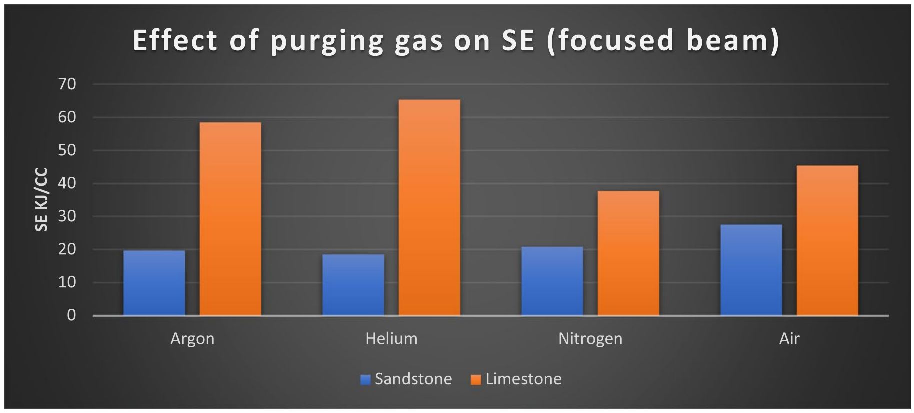

Fig. 7 Effect of various purging gas types on SE (focused beam) [2, 34]

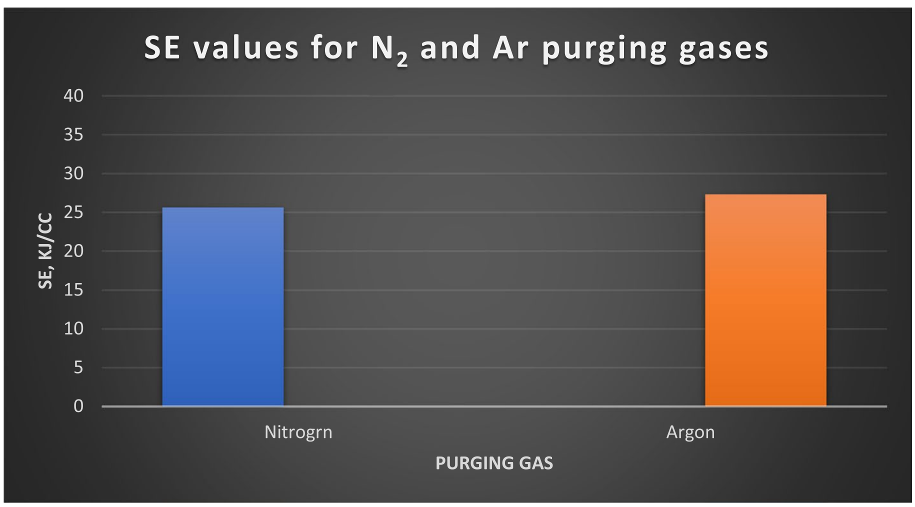

Fig. 8 Evaluation of nitrogen and argon as purging gases for COIL laser investigation [52]

limestone samples were positioned in a plexiglass tank and lased with a 5.34 KW HPFL with a spot size of 0.35 inch. The purging system utilized a liquid pump to circulate the purging liquid and tubes with nozzles to direct the purging fluid to the lasing point. Various nozzle shapes were tested for optimization.

In the first stage of this investigation, samples were lased by a 5-KW power for a duration of up to 10 s with two directions (angles) of the liquid purging fluid coinciding or in a perpendicular direction with the laser beam at the lasing point. In the latter case, the laser beam will penetrate the liquid flow before interacting with the sample. No sizeable penetration was observed in the rock samples under both application modes for water or anti-freeze liquid purging fluids. Laser beam energy causes water vaporization, where the anti-freeze liquid absorbed beam energy and reached its flash point [34].

The second experimental stage targeted investigating the effect of beam duration and power on lased samples under a liquid purging system. In testing the effect of beam duration, lasing duration was varied from 4 to 10 s with 2-s increments in a set of laser shots. The resulting SE variation with beam duration was as shown in

Fig. 9A. Another set of shots was applied to investigate the effect of beam power, where the power level was varied from 40 to 100% with 20% increments, for a 4-s beam duration. Figure 9B illustrates the resulting variation in the SE values with beam power variation [32]. The recorded SE values for liquid purging fluid were higher than those recorded under the application of the gas purging system. Limited pump capacity may be one of the possible reasons for these higher SE values because the pump provided a lower magnitude of purging force compared to the utilized gas purging system with a 90-psi tube pressure [34].

The liquid purging system may require more experimental investigation to provide a better understanding of the increased complexity related to the experiment. One of the proposed tests involves applying the purging fluid at various angles rather than 0 and 90° relative to the beam axis which may result in different clues and worth being tested. Another proposal to reduce complexity and energy loss is to use a laser head that is submerged in the liquid purging fluid. Moreover, using non-Newtonian fluids with rheological properties is worth being tested to evaluate the effect of rheological properties

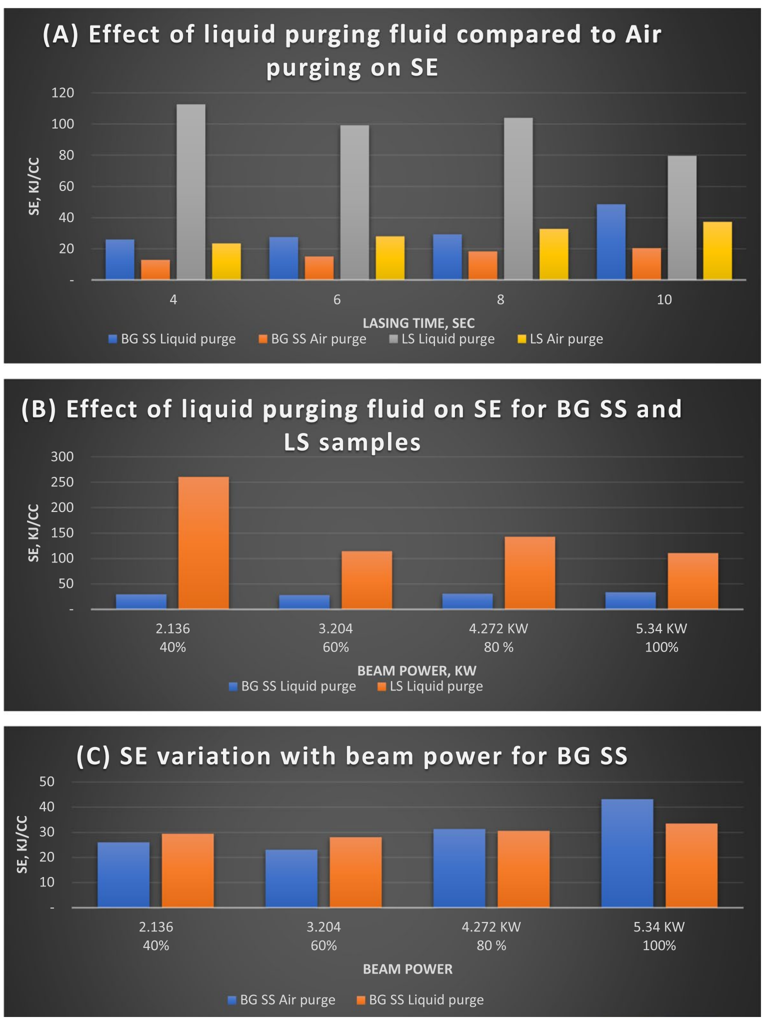

Fig. 9 **A** Effect of beam duration on the SE of liquid purging system compared to gas purging system for BG SS and LS. **B** Effect of beam power on the SE for BG SS and LS for liquid purging fluid (beam duration 4.0 s). **C** Effect of beam power on the SE of BG SS for both liquid and gas purging system (beam duration 4.0 s) [34]

on the cutting process. This may require developing additives that can produce transparent and clear drilling fluid that can withstand the laser induced high-temperatures.

Beam energy losses are greater through liquid medium compared to the gas, so additional beam energy is required to compensate for such energy loss to provide the same beam intensity. This can be inferred from Fig. 9C which compares the SE values of both the liquid and gas purging systems; the optimum beam power (lowest SE) for the liquid purging system is shifted to a higher beam power value compared to the case of the gas purging system. At a higher beam power level, the liquid SE becomes lower than that of the gas purging system. The difference increases with more beam power. Optimum power is a function of a set of parameters and is dynamic, and interactive, so any change(s) in the parameters or variables can move the balance state and the optimization to another point. This is why it is recommended to initiate the optimum parameters for each experimental work individually.

The losses of beam power till reaching the target are complex and depend on beam power and intensity. For example, higher beam energy creates more vaporization that will block or reduce delivered beam power. Pulsed mode of laser beam may reduce this effect because it allows concentrated application of laser at a short time and provides time for re-cooling of the beam path and more purging. Another example, the delivery losses through fiber optics depend on beam power; in an experimental investigation, the actual measured delivered beam power ranged from 686 to 1310 W due to lower transfer efficiency for low energy pulses (2 J/pulse) [48]. The laser used for drilling lies in the infra-red region and longer wavelengths; the presence of certain components in the media may substantially increase beam power losses. This occurs due to the presence of power levels with an energy difference that equals the laser beam photon energy which is calculated according to [53]:

$$E = h\,\upsilon \tag{2}$$

where h is Blank's constant and υ is the photon frequency.

In fiber optics, energy losses can occur due to various reasons such as scattering, absorption, and bending losses. However, losses at specific wavelengths can be attributed to quantum phenomena such as Rayleigh scattering [50] and Raman scattering [54]. These effects can cause the light to scatter and interfere with the original signal, resulting in energy losses. The severity of these losses is dependent on the wavelength of the light and the properties of the fiber. This quantum behavior requires careful choice of laser type (wavelength) that will suffer the lowest losses during transfer to the rock.

A liquid purging system can provide better purging due to higher viscosity and density compared to gases. Moreover, higher thermal specific energy and latent heat of vaporization compared to thermal specific energy in the case of a gaseous purging system can facilitate heat dissipation at lasing point, which will reduce melt formation and reduce the SE value [2, 32]. However, liquid purging systems will exert greater downhole pressure compared to gas purging systems which will exert greater holding force on cut rock material and may in turn reduce the SE value.

Relative motion between the sample and the laser beam affects the purging system efficiency and the recorded SE. Preventing heat accumulation is very important to prevent phase changes and secondary phenomena that increase the SE value and reduce drilling efficiency. Four different beam application methods were considered and investigated. Besides linear track lasing of rock samples [12, 48, 55, 56], other laser application methods were discussed by XU, Zhiyue, et al. (Fig. 10) [2, 14, 57]. Three application methods of a continuous CO_2 laser beam on samples to create a 1-inch diameter perforation tunnel of 2–5-inch penetration depth were discussed where the first method involves a stationary beam (Fig. 10A), the second one involves circular motion beam (Fig. 10B), and the third method applies rotation of the sample (Fig. 10C) [57]. Testing the effect of rotational speed on perforation using Nd: YAG laser was discussed also by XU, Zhiyue, et al. [12]. Holes created by the three methods are shown in Fig. 11.

In the first method (Fig. 11A), the center of a shale cylindrical sample of 3″ diameter and 3″ thickness was shot by four laser bursts of 4.0 KW, fixed defocused CO_2 laser beam for 4 s per burst with a 1-inch diameter laser spot size while purging the sample with a 200 ft^3/h nitrogen gas discharged from a purging system that was composed of two symmetrical 65° purging tubes attached to the lasing head. Both the lasing head and purging system can be moved toward the lased sample to keep constant spot size. A 1″ clean hole of 2.9″ depth was drilled by the first three shots with an average ROP of 72.5 ft/h. The fourth burst resulted in sample cracking and melt formation at the bottom of the hole which reduced hole depth to 2.85″. Each burst of the first 3 shots created a hole of about 0.967″, and the head was moved 0.5″ toward the sample after each shot. Such behavior of sample upon lasing demonstrated that

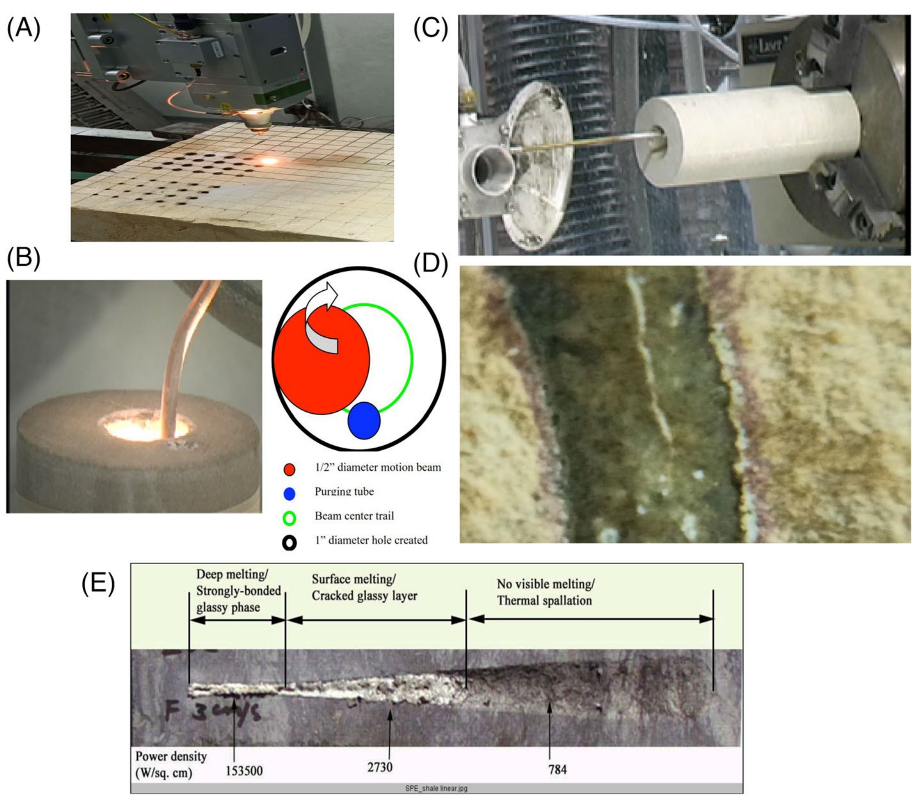

Fig. 10 Laser drilling and perforation application methods. **A** Stationery beam lasing SS sample. **B** Circular motion beam lasing shale sample. **C** Rotating sample. **D** and **E** Linear track ((**A**) and (**D**) [M. Hosin et al.]), (**B**) [57], (**C**) [14, 57], and (**E**) [12, 48, 55–57])

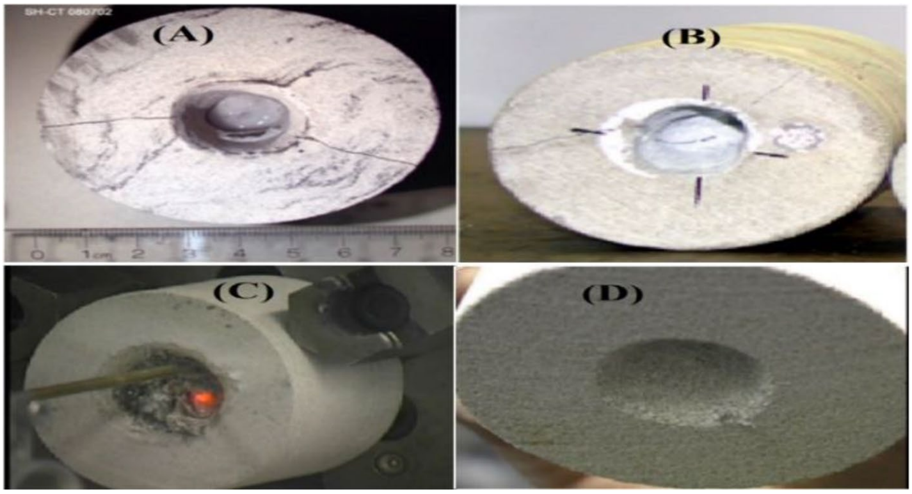

Fig. 11 Samples lased by three different methods. **A** Stationery beam (shale). **B** Circular motion beam (LS). **C** and **D** Rotating sample (SS) [57]

the first method applicability is limited to shallow hole depths (< 3″ in depth) due to limited purging system efficiency beyond this depth. Using a coaxial gas purging system may allow better purging efficiency and deeper effective penetration depth [52]. However, if the lased sample was limestone, this would not be the resulting behavior. Limestone shows lower fracturing and melting tendencies; this is because carbonates will be thermally dissociated at a temperature far low from the melting point with a dissociation rate that depends on temperature which means faster dissociation before heat accumulation to the melting point. It may require more energy and higher specific energy due to the energy consumed in the thermal dissociation but can reach deeper penetration depth effectively. Moreover, sample size plays an important role in fracture behavior. It would be better if the sample was of 4″ diameter or larger to avoid boundary effects. Pulsed beam mode would result in higher clean penetration depth because pulsation gives more time for the purging system to clean the beam path and reduce heat dissipation away from the lasing point. Yet, this will be valid for a certain depth where the purging system effect will be too weak for cleaning. Using a collimated beam would assist in creating a deeper hole because beam intensity is constant with penetration depth [57].

The second method (Fig. 11B) tests the application of the beam with circular motion relative to the sample created by placing the sample on a rotating workstation. A tapered hole of 5 inches in depth and 1-inch diameter at the hole entrance and 0.2-inch diameter at the end of the hole was created in a limestone core sample of 4 inches in diameter and 6 inches in length, lased by a 4 KW, a defocused CO_2 laser beam of 0.5-inch spot size that rotates around the center of the one-inch circle where 1-inch hole diameter will be drilled after one complete revolution as shown in (Fig. 11B), the purging system tube was placed inside the created hole, moved toward hole bottom by half an inch after each revolution (burst), and circled with the beam to provide a strong constant purging at lasing point with a flow rate of 300 ft^3/h. The linear relative motion speed was 50 in./min. Placing the purging tube inside the hole allows better purging as hole depth increases, while circular motion provides time for lased point to cool during circular motion back to lasing point. The result will be a deeper clean hole with a lower degree of overheating or melt formation. However, constant change between lasing point and sample center occurs leading to creating an asymmetrical hole. Moreover, as the hole gets deeper compared to the hole diameter (5:1 in this experiment), the secondary energy absorbing phenomena related to created fumes and ineffective purging of cut rock is increased, which assists in tapered hole formation. Compared to the first method, a deeper hole was created due to the better purging efficiency, lower accumulated temperature resulting in a lower degree of melt because of the relative motion, the effect of increased beam intensity, and the less fracturing tendency of the limestone samples [57].

In the third method, the rock sample was clamped to a rotary chuck to provide rotation around the sample axis where a stationary, 0.5-inch diameter, continuous, defocusing $CO_{2,}$ horizontal laser beam, and a 1/8-inch purging tube was placed 1/4 inch away from the core axis. After each lasing cycle, the laser head was moved toward the core to keep the constant gas flow and spot size at lasing point and compensate for the drilled depth; 275 ft^3/h of nitrogen gas was applied for purging. Four rotary speeds (2000, 3000, 5000, and 10,000°/min) and two laser power levels (2.5 and 4 KW) were tested. The higher the power level and/or lower rotational speed, the more heat accumulation and temperature increase, and in turn the more (glassy) molten material formation with reduced cutting efficiency and higher specific energy (Fig. 11C). Lower beam power and/or higher rotation speed resulted in lower melt formation (Fig. 11D). The optimum application conditions of this experimental setup were found to be 2.5 Kw beam power and 10,000°/min rotary speed, which were utilized for creating a 1″ perforation hole in a 3″ diameter, 7″ thickness sandstone sample as shown in Fig. 10C. After 45 s, a 3.3″ depth hole was created with diameter reduced from 1″ at hole entrance to 0.5″. This behavior is due to the increased beam attenuation caused by secondary effects with increased hole depth. A collimated laser beam with a better purging system can improve and increase perforation tunnel geometry and depth [52]. The three methods discussed can create clean perforation holes to a certain depth, depending on efficient beam delivery to the lasing point, beam shape and intensity, efficiency of purging system, heat accumulation at lasing point, and type, mineralogy, composition, and size of lased rock [57].

In the fourth application method (laser beam was applied under linear track motion), slab samples of BG SS, Ratcliff LS, and Frontier shale were moved in a linear track at a constant speed, while the laser head position was raised from 0.5 to 20 cm away from the surface of the sample. This application method allowed continuous testing of a wide range of parameters as is detailed in Table 1. The variations in the actual measured delivered beam power are attributed to the variation of delivery losses through fiber optics with beam power where the transfer efficiency was lower at low pulse (2 J/pulse) energy [48]. The resulting ablations created by the linear track tests are shown in Fig. 12.

Table 1 Range of change in lasing parameters during linear track lasing tests [48]

Item	Range of change
Laser head position above the sample	0.5–20 cm
Beam spot size	0.5–22 mm
Energy per pulse	2–32 J
Repetition rate	50–800 Hz
Average power	1.6 KW
Peak power	4–16 KW
Pulse width	0.5–2 ms
Actual measured power delivered	686–1,310 W

Effect of rock parameters on the laser drilling process

Effect of rock type on specific energy (SE)

Yang et al. (2020) used basalt, granite, and sandstone samples to test the effect of rock type on the lasing process. Basalt and granite are hard rocks, while sandstone, limestone, and shale are very common formations in oil well drilling that entail comparable characteristics. Unconfined compressive strength values were presented by many authors [58–61]. Table 2 presents average rock strength values (MPa) for some common types of rock. The tested samples were 4.5 mm × 4.5 mm × 3.5 mm

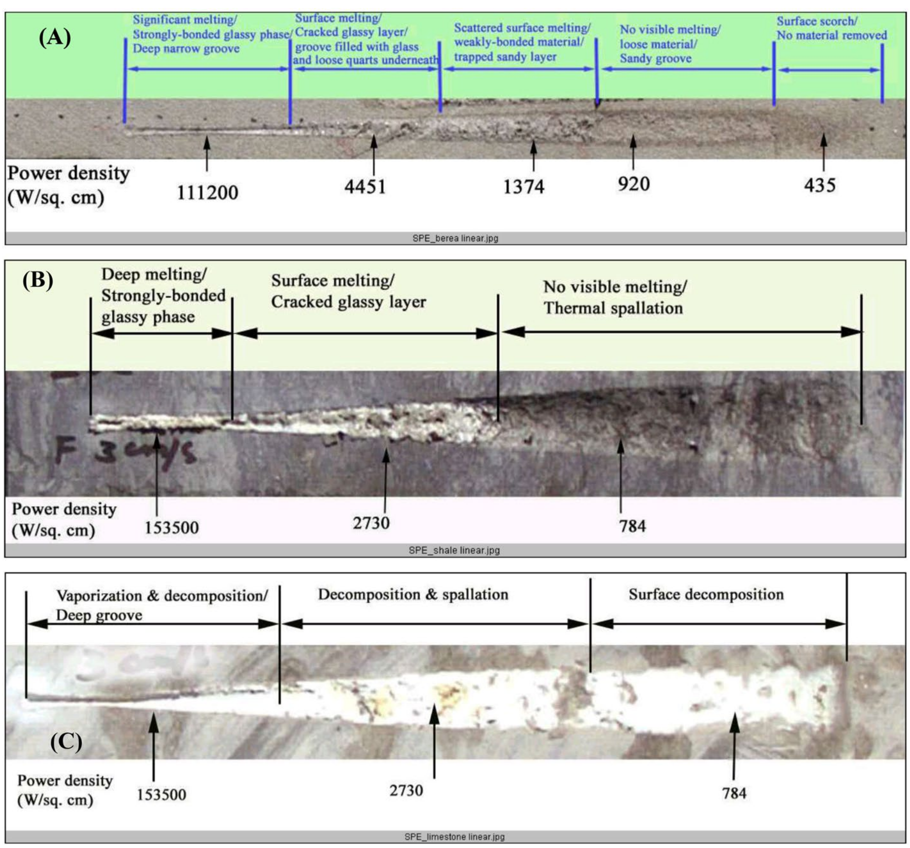

Fig. 12 Linear track lasing test of **A** BG SS with (5 melting and spallation zones), **B** Frontier shale (3 melting and spallation zones), and **C** Ratcliff LS samples (3 melting and spallation zones) [48]

Table 2 Compressive strength values (MPa), thermal conductivity, thermal expansion coefficient, and melting and vaporization point for some common types of rock [59, 62–65] (www.geology.com, www.AZoM.com)

Rock type	Granite	Basalt	Lime stone	Sand stone	Shale	Quartzite
Compressive strength range (MPa)	130–300 [62]	100–300 [62]	30–250 [63]	15–120 [62]	5–50 [64]	120–300 [65]
Average compressive strength (MPa) [59]	181.7	214.1	120.9	90.1	103	288.8
Thermal expansion coefficient range (10^{-6}/°C)	7–10 [62]	7–10 [62]	8.4–11.2 [63]	8.2–13.9 [62]	7–12 [64]	12–14 [65]
Thermal conductivity range (W/mK)	2.6–3.0 [62]	2.7–3.3 [62]	1.33–2.87 [63]	1.31–2.13 [62]	1.1–2 [64]	5–7 (www.geology.com)
Melting point (or range) °C	Depends on composition (1200–1710)	1100–1200 [65]	Decompose @ 825 °C before reaching the melting point [682]	1,710 (www.geology.com)	1000–1300 [65]	1650 (www.AZoM.com)
Vaporization point (or range) °C	-	2800 [65]		-	-	2800 (www.AZoM.com)

in dimensions. A laser beam of 50 W was focused by 160 mm focal length lenses to achieve a 2.0-mm spot size on the sample face with laser beam power and duration varied for evaluation. The results of this experimental work on basalt, granite, and sandstone are shown in Fig. 13, which indicated approximately similar drillability for both basalt and granite as that for sandstone, and in consequence, the influence of rock type on laser drilling is negligible [1–3, 9, 10, 37]. Figures 13A and B show the effect of beam power and lasing duration on the depth of the laser-drilled holes. As expected, increasing beam power or lasing duration resulted in deeper holes, but with a non-linear relationship, because additional beam power or lasing time results in phase change together with other secondary phenomena [2]. Increasing heat accumulation, more powerful beams, and/or longer exposure time may result in melting the rock. Such melting not only consumes beam energy; the molten material further decreases the efficiency by reflecting some of the incident beam energy backward at the surface. The purging system efficiency presents an additional reason behind these nonlinear relationships as the deep holes reduce the efficiency of hole cleaning and enable the development of fumes and gases. Such accumulated cuttings and gases absorb a reasonable portion of the beam energy and inconsequence reduce efficiency. Moreover, for focused beam shots with a stationary lasing head, beam spot size and intensity are continually changing with more depth of hole created; such changes depend on the relative position of the sample to the beam focal point; moving away from the focal point in both directions increases spot size and reduces beam intensity and vice versa. The same effect applies to ROP. The diminishing intensity of the laser beam will reach the threshold value at a certain depth where no more cutting action of the laser will exist.

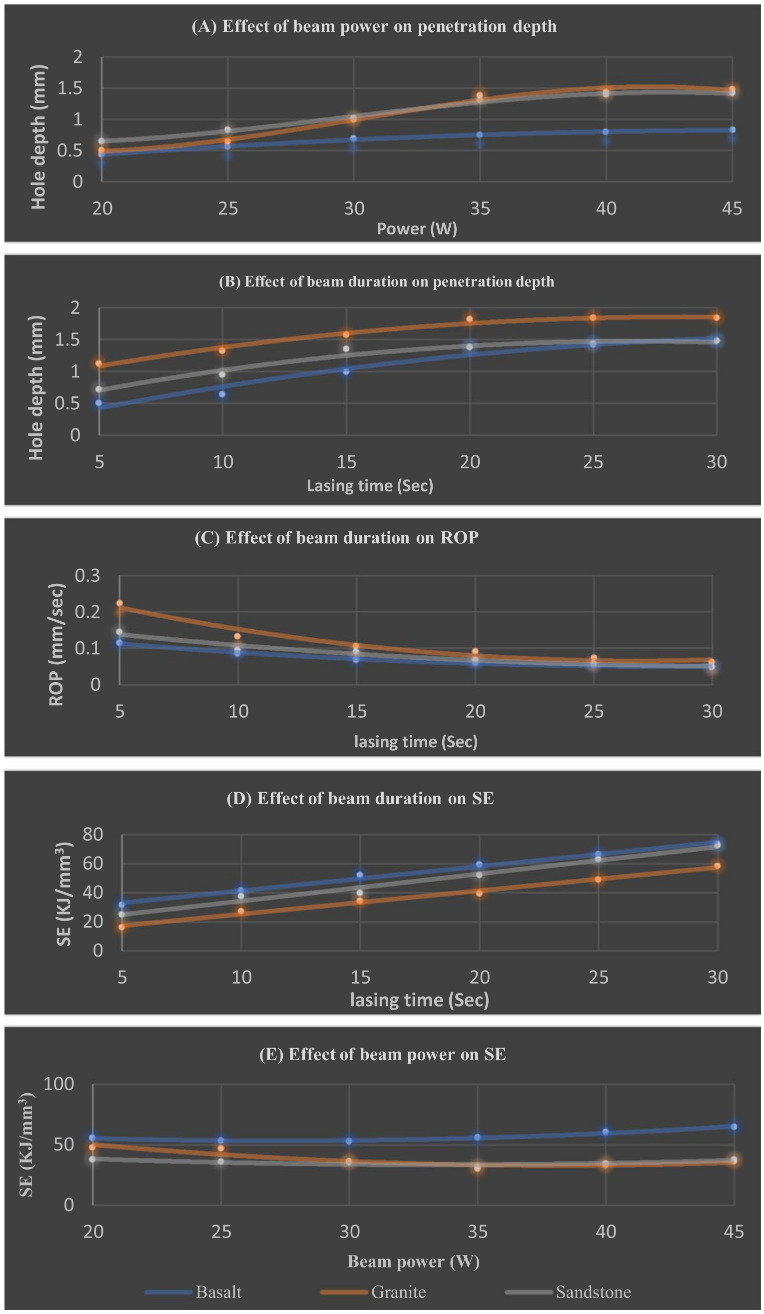

Fig. 13 Effects of **A** beam power and **B** beam duration on penetration depth, **C** beam duration on ROP, **D** beam duration, and **E** beam power on SE [10]

The effect of beam duration on ROP is presented in Fig. 13C. Beam power will also have the same effect on ROP. This can be explained by considering the melting and other secondary effects related to a higher power beam or a longer lasing time. Lower beam power or shorter lasing time results in higher ROP because almost all beam energy is consumed in the cutting process only. With additional power or lasing time, the drilled holes get deeper with the development of molten material due to lower purging efficiency. The effect of beam duration on SE is presented in Figs. 13D and 14. Figure 13E

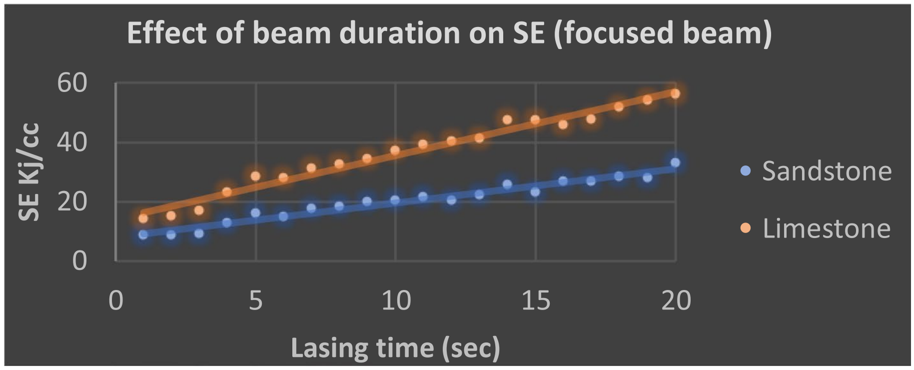

Fig. 14 Effect of beam duration on SE for LS and SS [66]

shows a linear relationship between the beam duration to SE and indicates that granite is drilled easier by laser compared to both sandstone and basalt. Also, sandstone was drilled with less power compared to basalt. Figure 14 shows the effect of beam duration on SE recorded for Brea sandstone and Bedford limestone samples lased by a 5.34-Kw high-power fiber laser (HPFL) in another experimental investigation [34] (www.materion.com). SE variations could be due to variations in rock strength, changes in dominant mineralogy, chemical interactions initiated by laser beam, delivered heat, and/or other factors. Rock strength determines the thermal stresses required to detach the rock cuttings because the thermally induced mechanical stress must exceed rock strength through the destruction process. Thermal expansion at the lasing point is constrained by the surrounding of the lased points, so mechanical stress arises and increases with more heating that eventually reaches the failure point where the rock will be cut. The magnitude of mechanical stresses can be calculated by multiplying the Young's (or Bulk) modulus and the induced thermal strain. Figures 15 and 16 show the effect of beam duration on SE recorded for Brea SS and Bedford LS lased by HPFL for 4 and 8 s [34] (www.materion.com).

Rock mineralogy affects the behavior of lased rock. For example, some minerals will thermally decompose to other components consuming energy such as the thermal decomposition of carbonates, limestone, dolomite, and magnesite [67]. Therefore, if the rock is mainly sandstone with a percentage of limestone, some of the lasing energy will be consumed in the thermal dissociation of limestone rather than the cutting process.

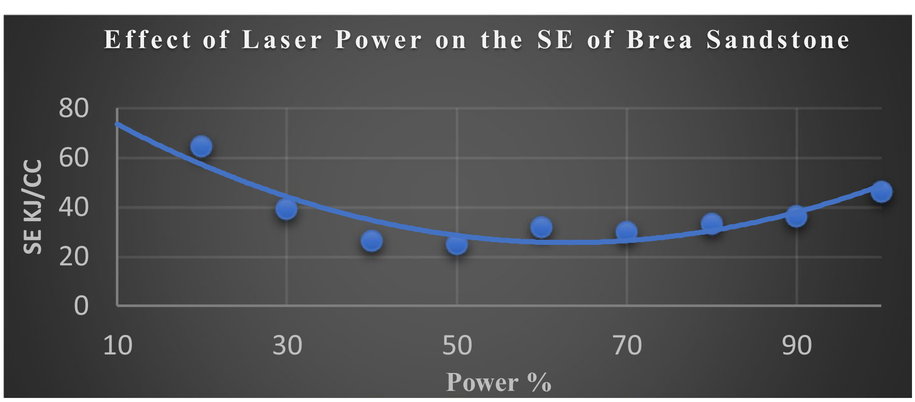

Fig. 15 Effect of beam power on SE for Brea SS, focused beam, beam duration 4 s [34, 66]

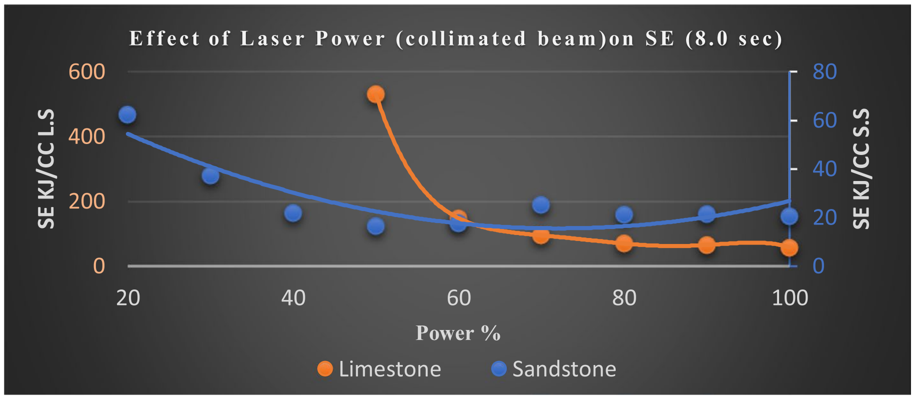

Fig. 16 Effect of beam power on SE for Brea SS and Bedford LS, collimated beam, 8-s lasing duration [34, 66]

Mineralogy also affects rock thermal properties which in turn affect the heating process; different minerals have different thermal properties that affect thermal propagation and response within the rock. Chemical interactions can be initiated due to heating, especially thermally endothermic reactions. These reactions can produce gases resulting in pressure that assist in rock drilling, as is the case if a percentage of carbonates exists in the lased sandstone. It also can result in denser products, causing fissures and cracks in the rock matrix that also help in the drilling process, as the dolomitization process. This concludes that the laser beam delivers heat to the lased rock point and the resultant thermal behavior is affected by other factors such as the purging system and rock composition. The resulting interaction of all these factors affects the drilling process, and all these parameters have to be optimized for effective drilling of each case [10, 23, 24, 68–75].

One of the other experimental investigations on the effect of rock type on SE, lased 240 rock samples of different lithologies [Brea sandstone, Ratcliff limestone (cored @ 6,000 ft.), Frontier shale (cored @ 13,200 ft), salt, granites, and concrete], with three different laser types [Mid-Infra-Red Chemical Laser (MIRACL), chemical-oxygen-iodine laser (COIL), and carbon dioxide (CO_2) laser] [48]. The investigation results assured that rock type has little effect on laser drilling because much SE variation was observed within the same lithology as between different lithologies [2, 10, 11, 48, 68]; however, shales, in particular, recorded SE values that were an order of magnitude less than those recorded for sandstone or limestone [48]. Moreover, limestone SE variations were of the least value; this is attributed to no melting occurrence where only thermal dissociation occurs at a temperature (around 825 °C) far below the melting point (around 1100 °C). The rate of thermal dissociation increases with additional temperature, for example, a 10 °C increase in temperature increases the decomposition rate five times. A larger SE value is noticed for limestone samples at beam power or duration, because the temperature developed was not sufficient for initiating thermal dissociation at a considerable rate, with more heat lost to the environment or in other processes, and after raising the beam delivered power, SE variation is low.

M. Hosin et al. investigated the effect of rock type on SE for various samples such as Hashma SS, Pharaonic LS, granite, marble, concrete, gravel, and tiles using 6 KW HPFL at CMRDI, using air and nitrogen nozzle gas purging system, and concluded that the variation in SE for the various lithologies is of the same magnitude within and between lithologies, with different optimum condition sets for each type.

Figure 17 shows how the SE values varied for both continuous or chopped beam modes for various lithologies obtained in another experimental investigation [52], where the formation variation effect on the SE value is low. Figure 18 presents SE variation with rock type at various beam powers. Dry core plugs of various formation types such as salt, limestone, shale, Brea yellow, Brea grey, sandstone, and granite (white and feldspar) were lased by COIL laser at three power levels of 35, 50, and 100% for 8 s. The results show that the SE values for the various lithologies at the three tested beam power levels are in the same range of 10–40 kJ/CC. Figure 18 presents SE variation with rock type at various beam powers obtained in another experimental investigation [52]. Dry core plugs of various formation types such as salt, limestone, shale, Brea yellow, Brea grey, sandstone, and granite (white and feldspar) were lased by COIL laser at three power levels of 35, 50, and 100% for 8 s. The results

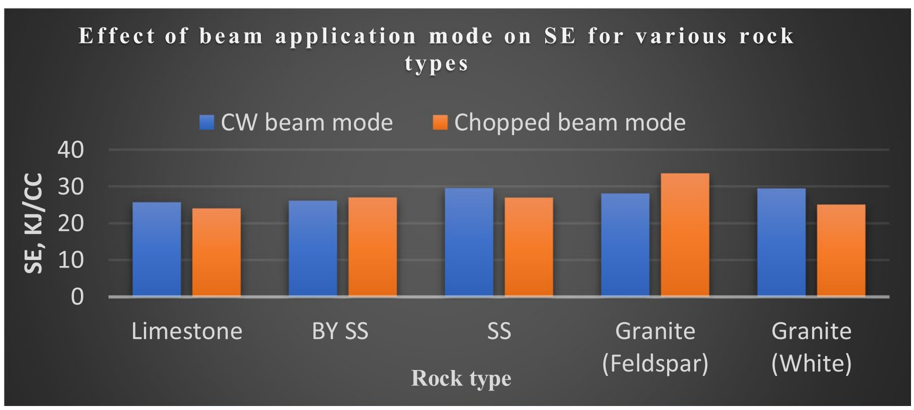

Fig. 17 Effect of beam application mode on SE for various rock types [52]

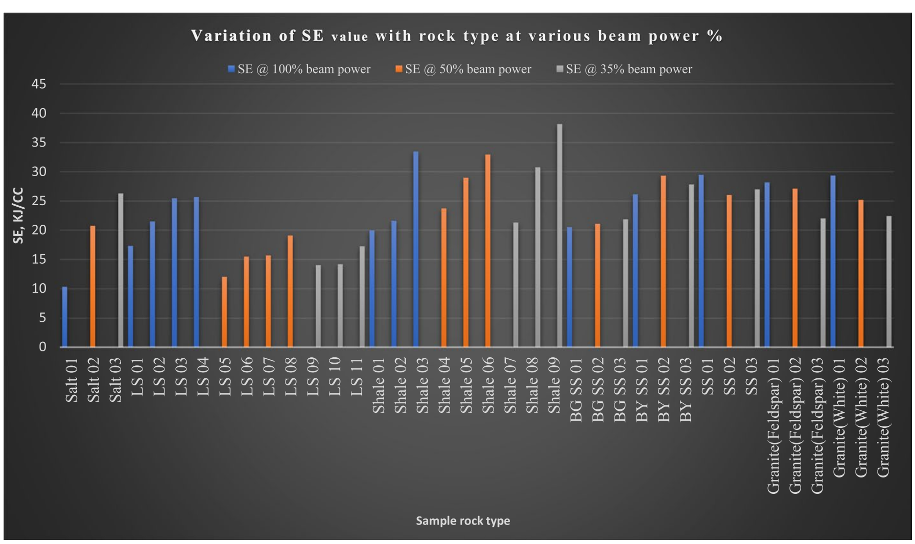

Fig. 18 Effect of rock type on SE at 100, 50, and 35% beam power [52]

show that the SE values for the various lithologies at the three tested beam power levels are in the same range of 10–40 kJ/CC.

Effect of sample size (boundary conditions) on specific energy (SE)

The effect of boundaries (sample size) on SE has been studied, where cores of sandstone and limestone of various sizes were lased, and subsequently, the SE was calculated using the weight difference method for each hole [2, 10]. Samples of 2.0 in. length and diameters of 0.75 (for SS only), 1.0, 2.0, 2.75, 3.0, and 4.0 in. are tested in this study. Each sample size was lased three times, and the average SE of the three shots was calculated. The utilized purging system was an optimized gas nozzle purging system with 90 psi gas pressure, 0.25 in. nozzle, 1.0 in. distance to the sample, and 35° purging angle. The laser parameter of 1.0 in. collimated, CW mode of 5.34 kW beam was focused by a lens of 39.37 in. focal length to create a laser spot size of 0.35 in. on the sample face for 8.0 s. Figure 19 presents that the SE is inversely proportional to the sample size with an exponential trend for both sandstone and limestone samples. Smaller samples were heavily fractured in the lasing process, and as the sample size increased, the intensity of the fracture was decreased. Macro-cracks were not observed for samples with a 4.0 in. diameter or more [1]. The development of fractures in the sample acts as an extra source of energy loss because each fracture plane acts as a new rock surface where some beam energy is reflected and/or scattered. Additional fractures lead to extra-energy losses, which increase SE.

Alternatively, in large samples, the boundary effect is far from the lasing point, and in consequence, the samples act as a large thermal dump. Furthermore, sandstone has a higher fracture tendency than limestone (Fig. 20), which may explain the wider variation in SE with size for sandstone compared to limestone samples (Fig. 19). This can be further explained in terms of the factors affecting fracture behavior.

Effect of sample orientation on specific energy (SE)

To evaluate the effect of sample orientation on SE, sandstone, and limestone cubes, respectively, 3.94 in. and 1.97 in. side length, were lased on each face; then, the SE for each hole was calculated [2] (www.materion.com). The optimized gas nozzle purging system comprised 90 psi gas pressure, 0.25 in. nozzle, 1.0 in. separating distance to

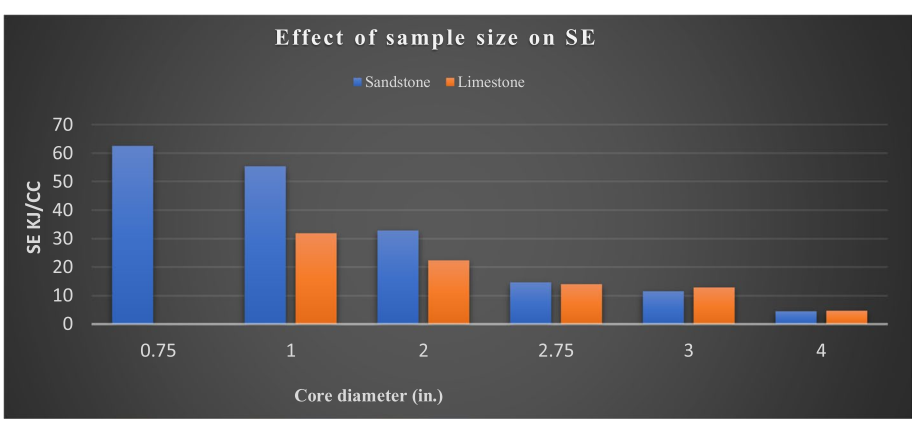

Fig. 19 Effect of sample size on SE [2, 34]

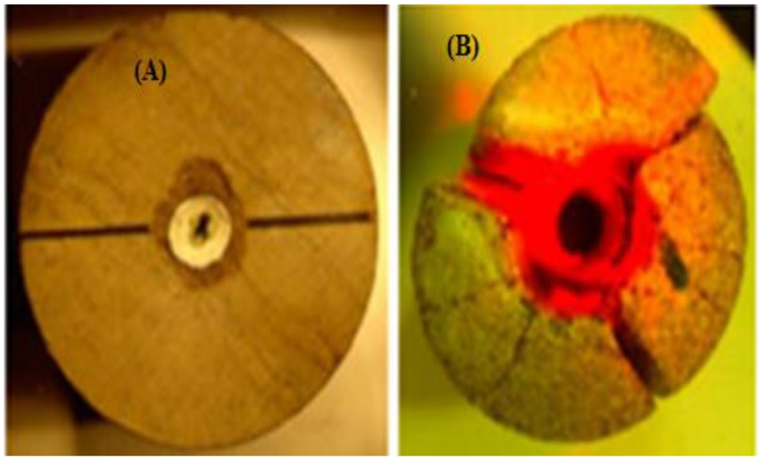

Fig. 20 Post-lasing fracture for LS (**A**) and SS (**B**) [3]

the sample face, and 35° purging angle. Laser parameter of 1.0 in. collimated beam, CW mode of 5.34 kW was focused by 39.37 in. focal length lenses to create a laser spot size of 0.35 in. on sample face for 8.0 s. SE value for each shot for both sandstone and limestone cubes was calculated and presented in Fig. 21. The results showed that sample orientation has a negligible effect on SE values [2] (www.materion.com). This behavior can be explained by the rock-breaking mechanism for sandstone and the thermal decomposition of limestone, which does not depend on orientation. Heat addition to rock is a scalar quantity; thermal expansion occurs in all directions and eventually causes fracture according to the in situ stresses and rock strength. Therefore, for sandstone, this experimental work could be incomplete due to equal applied stress in all directions. For limestone, a similar concept of heat addition applies, but the thermal dissociation is a chemical process, and therefore, a negligible effect of sample orientation is expected. Another investigation supporting the low influence of

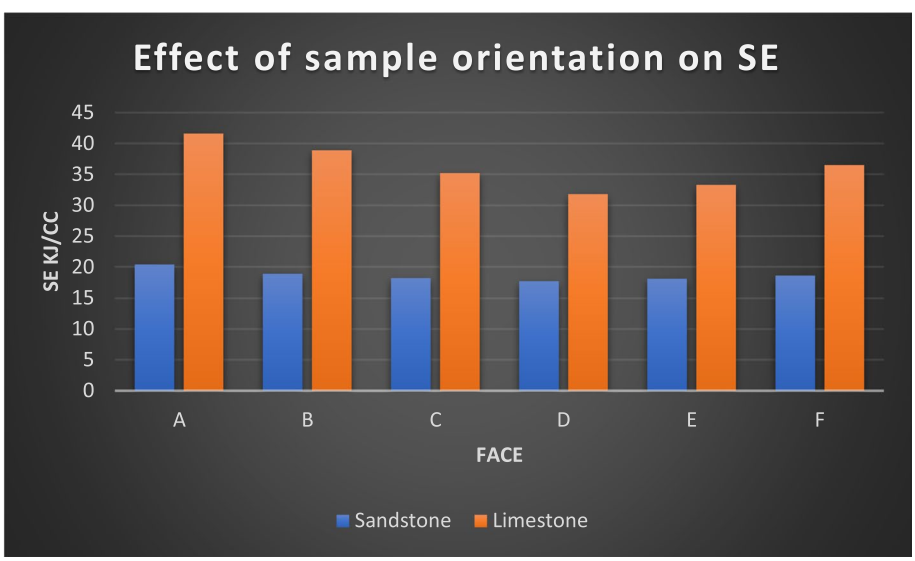

Fig. 21 The effect of sample orientation on SE [66]

relative beam orientation on SE was performed by M. Hosin et al. where samples were shot from various sides and in a random direction through the sample.

On the contrary, one of the experimental investigations recorded higher change when shale samples were lased for 8 s by a CW, COIL laser, where the vertical laser shot recorded a 50% increase in the SE value compared to the horizontal beam shot (Fig. 22). Variations of the SE values for both vertical and horizontal beam application modes for the chopped COIL beam on various rock types are shown in Fig. 23, where the vertical SE values were higher than the corresponding horizontal SE values [52]. This difference may be due to stronger boundary influence at vertical shots due to sample dimensions and shape.

Effect of saturating fluid on specific energy (SE)

To evaluate the effect of fluid saturating the rock pores on SE, sandstone and limestone cores of 2.0 in. diameter and 2.0 in. length were 100% saturated with water (fresh or brine), oil, and gas. To saturate a sample with a specific fluid, the sample was placed in a vacuum for six hours and then placed in a particular fluid for 24 h. After full saturation,

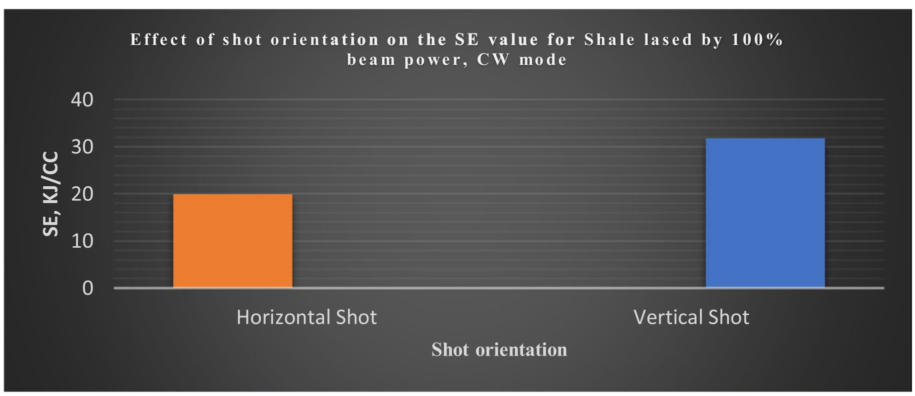

Fig. 22 The SE value for horizontal and vertical laser beam shots [52]

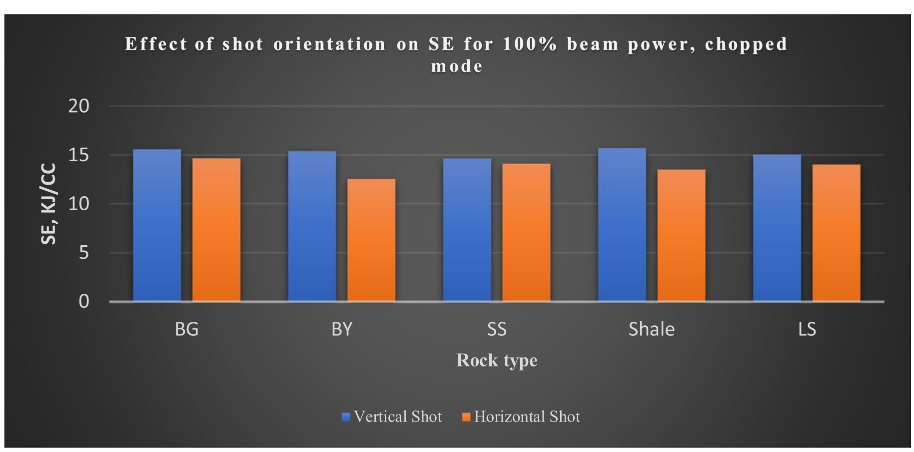

Fig. 23 Effect of sample relative position to chopped COIL laser beam at 100% power level for various formation types [52]

the sample is lased, and the SE of each shot was calculated. The brine has been prepared by dissolving 25,000 PPM NaCl and 25,000 PPM KCl in one liter of water. The specific gravity of this brine was 1.039, while the oil reported a specific gravity of 0.841. A plexiglass chamber was used to contain samples at downhole simulated conditions. The purging system deployed an optimized gas nozzle with 90 psi gas pressure, 0.25 in. nozzle, 1.0 in. separating distance to the sample, and a 35° purging angle. The purging gas was altered using argon, helium, nitrogen, and air, and the average SE value was calculated for each case. The laser parameter comprised a 1.0 in. collimated beam with a CW mode beam of 5.34 kW that was focused by a 39.37 in. focal length lens to create a laser spot size of 0.35 in. on the sample face for 8.0 s. For each saturation, the shot was repeated three times, then the average SE for three shots was calculated, and the results are presented in Fig. 24.

The results obtained from this investigation clarified that the dry samples have lower SE values compared to the saturated rock samples. It was also found that the sandstone samples reported lower SE, as expected because the thermal decomposition of limestone requires more energy than thermal cracking. For both rock types, the fresh water-saturated sample showed lower SE than brine-saturated samples, and both samples reported lower SE compared to oil-saturated samples. Water and brine-saturated sandstone samples with air and argon as a purging gas showed a slight deviation from this trend (Fig. 24). Although additional energy is consumed in liquid vaporization, and the produced vapors absorbed a portion of beam energy and partially blocked the beam path which results in higher SE, the liquid-to-gas phase change of the saturating fluid results in great volumetric expansion which probably would help in the rock drilling and inconsequence tend to decrease SE [2, 3]. The interaction between laser and oil is more complex than laser interaction with water or brine.

Another experimental work investigated the effect of saturating fluid on the SE value for Brea yellow SS core plug samples lased by COIL with three different beam powers of 35, 50, and 100% for an 8-s duration. The samples were saturated with air, water, brine, crude oil, and natural gas. The SE value of each lasing shot is presented in Fig. 25. Again, the SE values of dry samples were lower than any other saturating fluid SE value. However, the variation in SE values is lower than the case for HPFL variations; in addition,

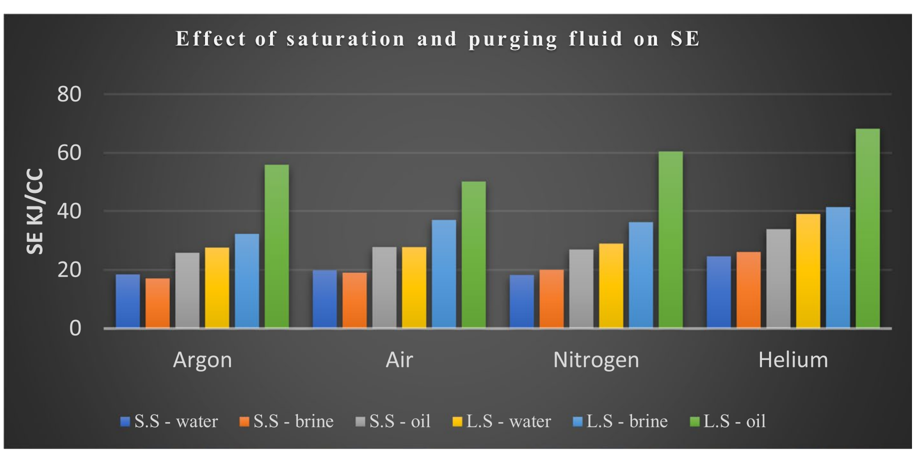

Fig. 24 Effect of saturation fluid on SE for various purging gases [2, 34]

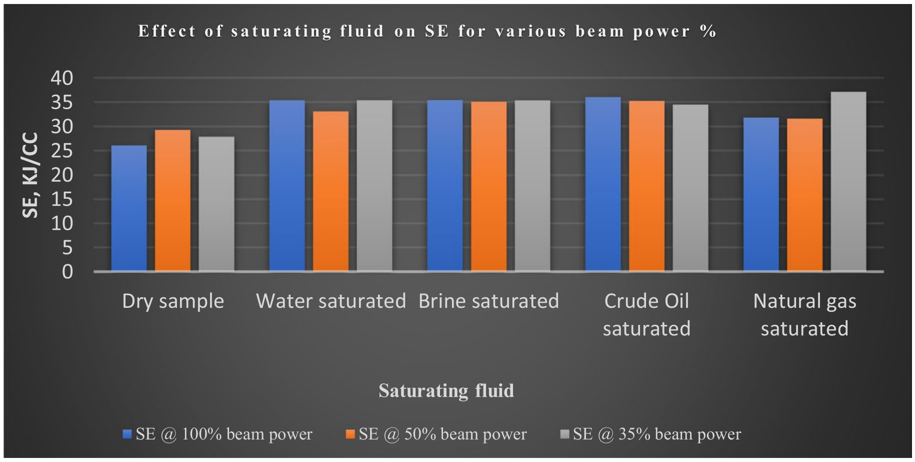

Fig. 25 Effect of saturating fluid on the SE values of Brea yellow SS for 35, 50, and 100% beam power [52]

the SE values for oil-saturated samples are in the same range for both water and brine-saturated SE values [52].

However, some experimental investigation results contradict the clue of dry and wet SE values described above. Where lower SE values were recorded for wet samples (Fig. 26) [2, 34]. These lower SE values for water-saturated samples may be a result of the better heat dissipation which in turn will reduce heat accumulation and reduce melt formation possibility at lasing point [9]. This point of view may be also inferred from Fig. 9C, where the SE of the liquid purge system becomes lower than that of the gas purge system with an increasing value difference trend. Again, water presence as a purging fluid or a saturation fluid requires further investigation as it has significant inherent complexity.

M. Ahmadi et al. [75] performed an experimental investigation on the effect of saturation fluid on SE of granite (as a high-strength rock) and limestone samples lased by pulsed Nd: YAG laser (at 41.25% beam power) with the experimental setup summarized in Table 3.

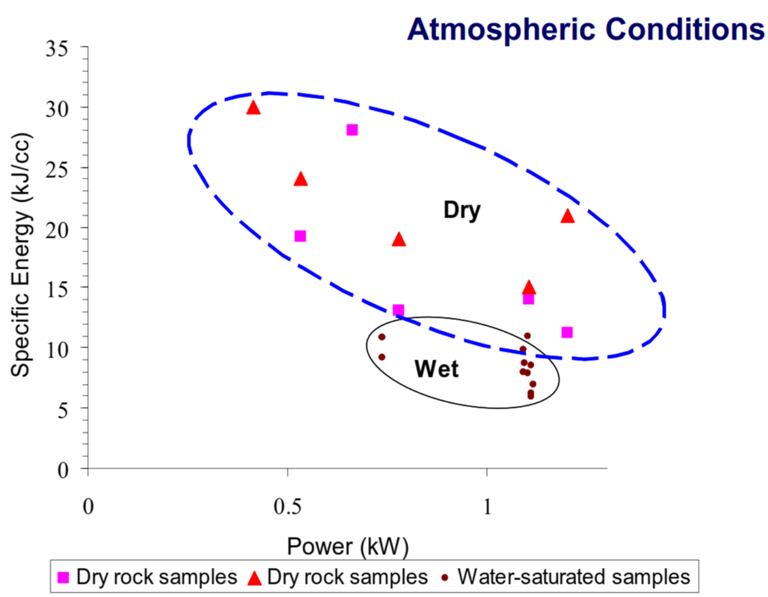

Fig. 26 The SE value for dry and water-saturated samples [2, 34]

Table 3 The experimental setup and parameters [49, 75, 76]

Laser parameters	Laser type	Nd: YAG (wave length: 1064 nm)
	Mode	Pulsed (square pulse)
	Mean power/frequency	400 W/1–1000 Hz (30 Hz used)
	Pulse energy/duration	0–40 J/0.2–20 ms (2 ms used)
Purging system	Purging system/gas/pressure	Gas nozzle/nitrogen/3 bar
	Nozzle size and orientation	1 mm—co-axial
Sample	Sample type, composition, and porosity (%)	Granite: 73.98% quartz, 26.02% dickite, 2.1% Limestone: 100% calcite ($CaCO_3$), 5.95%
	Shape (dimensions)	Cylindrical (diameter: 54 mm—length: 50 mm)
	Specific gravity of oil	0.92 gr/cc

The results are shown in Fig. 27 where dry samples recorded the highest hole depth with the lowest SE value and the highest ROP for both granite and limestone samples. On the other hand, water-saturated samples showed the lowest hole penetration and ROP, with the highest SE value for the lased samples. The results also showed that both the created hole depth and the SE value increase with beam duration, while ROP decreases as beam duration increases. This behavior is the result of the reduced beam intensity and increased secondary processes with longer beam duration. Increased beam duration increases, in turn, the created hole depth; thus, the focused beam intensity is reduced as the lasing point moves away from the focal point of the utilized focusing system; moreover, as the lasing point moves away from the purging system, more heat is accumulated and the efficiency of the purging system continue decreasing with the increasing hole depth from purging nozzle.

Effect of confining stresses on specific energy (SE)

The effect of in situ confining stresses on lased samples was investigated to detect the variation in the SE value and ROP compared to unstressed rock samples. Cuboid samples of BY SS were lased by COIL under various stress conditions, such as zero stress, vertical, horizontal, and simultaneous vertical and horizontal stresses, utilizing metal clamps [52]. It was observed that unstressed samples have lower SE values compared to stressed samples. The results also showed little effect of confining stress on the resulting SE value (Fig. 28).

Another experimental investigation which considered the effect of simulated wellbore pressure conditions on the laser perforation process was performed by applying axial, tri-axial (confining), and pore pressures on saturated core samples of sandstone and limestone with dimensions of 4.0 inches in diameter and 6 inches in length placed in a specially designed cell (rated 3000 psi and pressure tested to 4500 psi by manufacture) that allow applying up to 2,000 psi axial and confining pressure. The samples were lased by a 5.34 KW HPFL, in CW mode, for 8 s, with a constant beam spot size of 0.35 inch. Samples were saturated with oil or 50 PPM NaCl brine water for 24 h after they were placed in a vacuum for 6 h. A 90-psi gas nozzle purging system was used where pore pressure was not applied. In the first testing stage, a confining pressure of up to 2000 psi only was applied to the samples, whereas in the second testing stage, samples were subjected to, confining, axial and pore pressure up to 2000 psi.

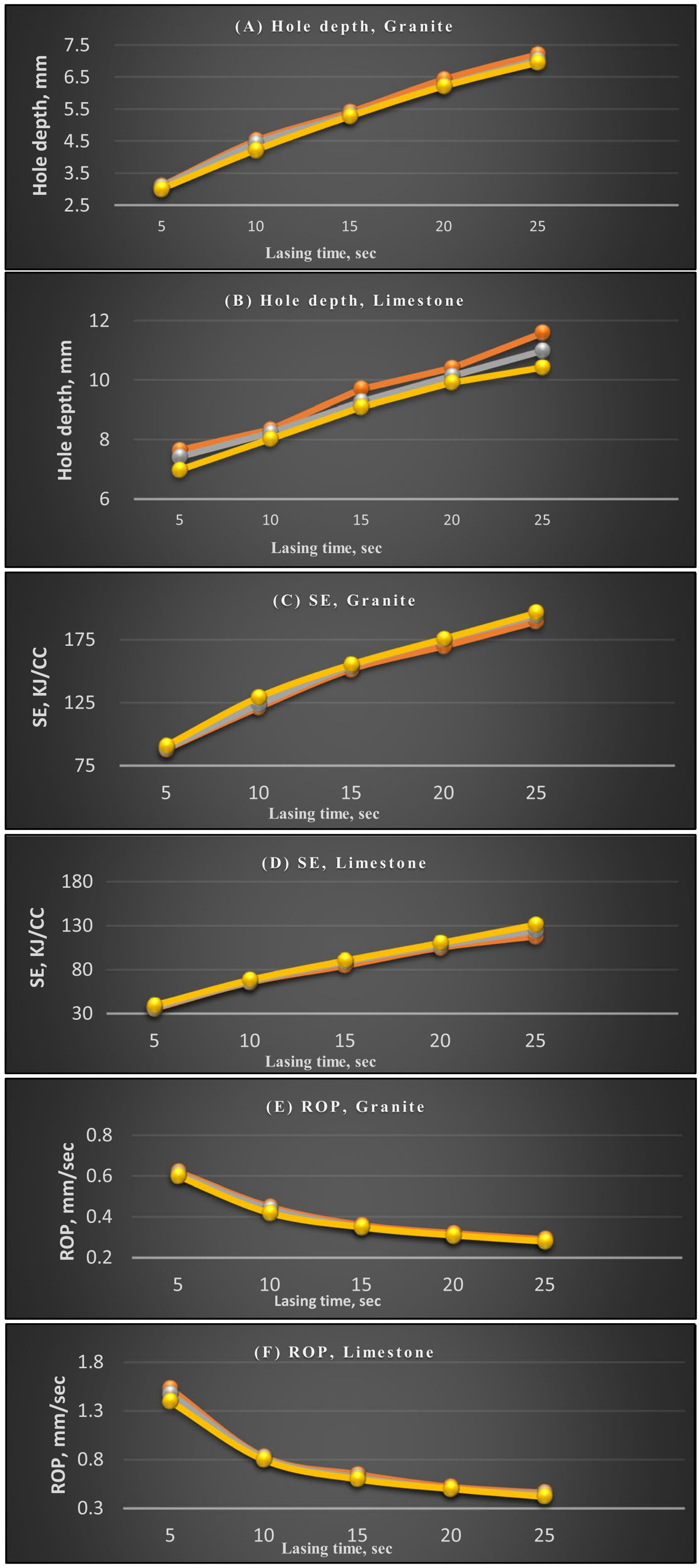

Fig. 27 The effect of saturation fluid on granite and limestone sample lasing process for dry (orange), water (yellow), and heavy oil (gray) saturated samples. **A** and **B** shows the created hole depth variation with lasing, **C** and **D** shows the SE value variation with beam duration, and **E** and **F** shows the ROP recorded for the lased samples [75]

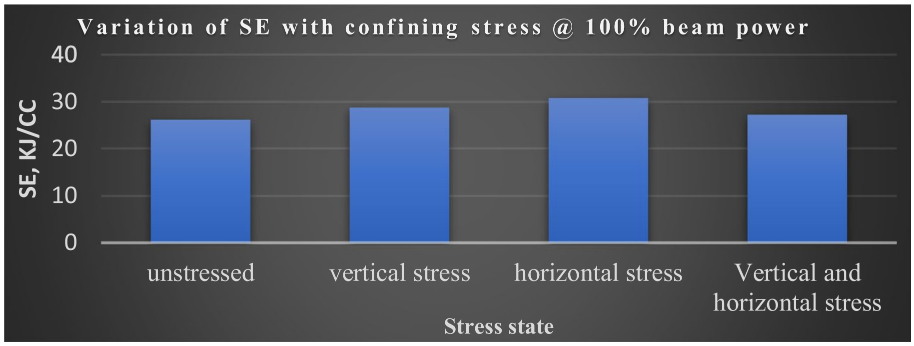

Fig. 28 The effect of confining stresses on SE [52]

Figure 29 shows the results obtained in this investigation, where a clean hole with no melt or cracks was formed under applied confining stress with a recorded SE value of 7.78 kJ/CC was compared to 18.2 kJ/CC for the stress-free lased sample [34]. Confining stress reduced fracture formation which is a source of energy loss. Moreover, as confining stress is applied, grains are closer to each other which results in a better heat transfer.

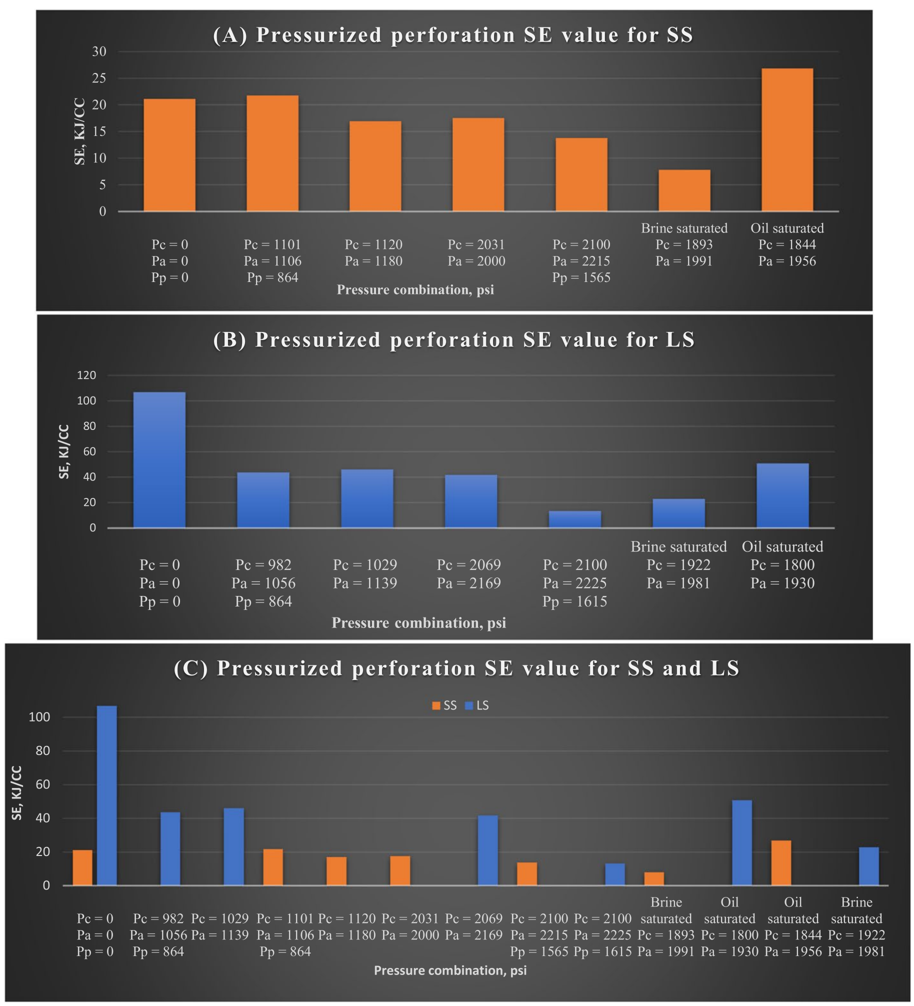

Fig. 29 Effect of confining (Pc), axial (Pa), and pore (Pp) pressure on SE value for **A** SS, **B** LS, and **C** both SS and LS, CW mode laser of 5.34 KW HPFL, 8 s lasing duration [29]

Heat is transferred through the rock matrix by conduction between grains, and convection by pore fluids.

External stresses applied to rock will cause deformation and compaction according to stress magnitude, pore pressure, saturation fluid, sample elastic properties, and strength. Surface or shallow-depth samples are relatively weak (low strength) due to a lack of sufficient overburden pressure during the rock's lifetime. So, applying higher confining stress can cause large deformation or fracturing in the sample according to elastic properties. This is why surface limestone samples were fractured upon applying confining stress (at 2215 Pisa) which exceeded its strength value. The externally applied stress forces rock grains closer to each other which also increases the contact area between grains. In limestone, this compaction increases heat transfer and, as a result, reduces SE value (Fig. 29B). For sandstone, compaction increases rock strength, and hence lower SE value reduction is recorded compared to limestone (Fig. 29A) [34]. Applying pore pressure (which represents the underbalanced effect) reduces the effect of confining pressure and helps in cutting removal.

Samples saturated with brine reported lower SE values compared to unconfined dry samples for both SS and LS lased samples. Although heat is lost to water during heating and vaporization, the tremendous increase in volume related to steam production creates high pressure at lasing point that help in rock cutting. Moreover, the presence of brine provides better heat dissipation leading to less thermal accumulation and lower temperature. This reduces secondary effects which consume a lot of beam energy and reduces the SE.

The laser beam interacts with the oil saturating the samples and produces dark clouds of fumes and vapors that in turn block the beam path and hence increase the SE value. On the other hand, brine interaction with the laser beam produces steam that was effectively removed from the beam path, and hence lower SE values were recorded for brine-saturated samples. Limestone samples' porosity values were lower than sandstone, so smaller (or even insignificant) oil and brine saturation volumes existed in the samples. These two factors explain why oil-saturated samples showed lower SE value for limestone, compared to dry samples; meanwhile, the opposite was recorded for sandstone. The results also spotlight the need for more experimental work devoted to studying the laser oil interactions to remove its inherent complexity.

Although low confining pressures showed little influence on the SE and other parameters [34], another investigation considered one granite and two limestone samples (from an Iranian oil and gas field) to evaluate the effect of high confining stress and saturation fluid on the SE value for an Nd: YAG laser type with the experimental parameters as presented in Table 3 [47]. The experimental setup used to apply various magnitudes of confining stress consisted of a Hoek cell equipped with a frame, where a top circular opening at the top was left to expose the sample to the laser beam. The Hoek cell allows applying a confining pressure to the side walls of the cylindrical sample using a hydraulic mechanism, while the frame fixes the sample in its position in the cell. Dry, water, and heavy oil-saturated samples (of granite and limestones 1 and 2) were placed under confining stresses of 0, 8 (1160 psi), 16 (2320 psi), 32 (4641 psi), and 37 (5366 psi) MPa and lased for 20 s. The created hole depth at various confining stress values for the three samples are shown in Fig. 30A, B, and C, while the SE and ROP values of the three samples were presented in (D), (E), and (F) and (G), (H), and (I). The results show that the created hole depth and ROP decrease with increasing confining pressure, while the SE values were

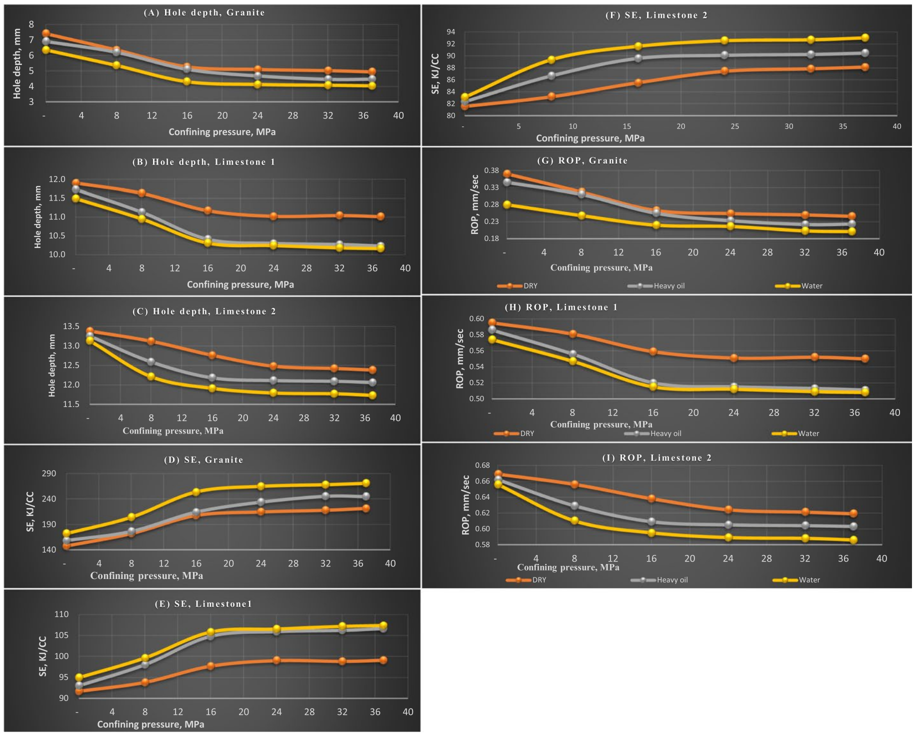

Fig. 30 Hole penetration, SE, and ROP results obtained for granite ((**A**), (**D**), and (**G**)), limestone 1 ((**B**), (**E**), and (**H**)), and limestone 2 ((**C**), (**F**), and (**I**)) [49]

increased. The rate of decrease/increase depends on the magnitude of applied confining stress where the 16 MPa was the changing point, with a higher increase/decrease for confining stress below 16 MPa, and the change is very low (nearly constant) beyond this value. The results clarified the effect of saturation fluid at high confining stresses where dry samples showed the highest hole penetration and ROP at lower SE value compared to heavy oil-saturated samples. Both saturation cases showed lower SE values compared to water-saturated samples with lower hole penetration and ROP.

The applied confining stress causes several changes to the rock matrix which result in different influences on the rock lasing process. Increasing confining pressure results in decreasing the macro-fracture formation which causes loss of beam energy, so the SE value is reduced. Increasing confining pressure also results in rock compaction which allows better thermal conductivity that reduces temperature accumulation at lasing point and hence will lower the temperature and reduces or prevents melting; this in turn reduces the SE value. However, for high beam energy, this heat dissipation may be extremely lower than heat accumulation, so a larger area of higher temperature will result in more melt formation rather than local melting or vaporization. This effect adds utilized beam energy as a controlling factor. On the other hand, increasing confining pressure increases rock strength, so more thermal stresses are required to overcome the increased rock strength and cut the rock. Higher confining stress will also affect the cut rock material, where the higher-pressure value exerts a greater chip hold-down force that will reduce purging system efficiency and hence will increase secondary phenomena which result in higher SE values. Increasing confining or ambient pressure on limestone increases the decomposition temperature and vice versa (Fig. 31) [77, 78]. In addition, the rate of decomposition increases with increasing confining pressure [78, 79].

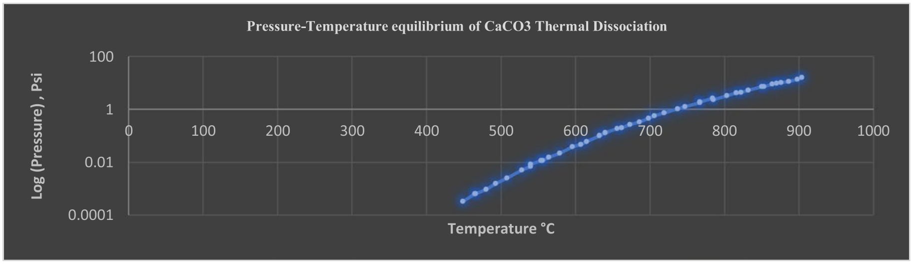

Fig. 31 The temperature–pressure equilibrium for the thermal dissociation of limestone [77]

Discussion

The gas amplifier system provides a uniform flow of the purging medium around the lasing point, while the gas nozzle purging system focuses flow at the lasing point. This results in efficient energy (lower SE), for laser drilling in sandstone or other rocks with a high melting point, because the focused gas flow is faster and more effective in cuttings removal and minimizing secondary phenomena which consume beam energy. Experimental results showed that using nitrogen as purging fluid results in optimal SE, the lowest for limestone, and almost the best among other inert gases for sandstone. Liquid purging fluids still require more experimental investigation to resolve inherent complexity. Moreover, non-Newtonian liquid purging fluids and their rheology require investigation for a better hole cleaning and to develop new additives that can cope with the laser cutting process and the accompanying high temperatures induced. Relative motion between laser beam and sample allows lower thermal accumulation and better purging of the sample surface with lower SE value recorded. The beam power has a great influence on the SE, while the spot size is of moderate effect on the SE value [80]. Different rock types were lased with various lasing parameters, and the results showed that laser can cut through hard and soft rocks with almost identical efficiency. Larger rock samples, > 4.0 in. in diameter, reported lower SE because the boundary effect is away enough from the lasing point. Experiments also showed that the relative direction between the laser beam and sample has a minimal effect on the SE which is very important for directional drilling and/or oriented perforations. In some investigations, oil-saturated samples showed higher SE values compared to freshwater or brine-filled samples due to the complex interactions between oil and laser beam which result in secondary energy losses; other investigations showed opposite results with lower SE values for wet samples. The effect of low confining stresses was found to be of minimal effect on lasing process where for large confining stress values, the higher the confining stress, the higher the SE value with the lower penetration and penetration rates; this is valid till certain confining stress values beyond which the effect is again minimal. The contradictions in results for liquid purging, saturation, and confining stress effects aim to the need for more experimental investigations to provide better understanding. Moreover, the optimum parameters are of dynamic nature. The tremendous number of factors contributing and affecting the laser cutting process have numerous interacting effects.

Conclusions

Laser can reduce the cost and time of oil well drilling and may improve the recovery of reserve. Laser-assisted PDC bits was applied in field since 2009 and proved application efficiency; the same system setup can be used to apply laser drilling for field applications. The purging system is of great importance to increase the efficiency of laser drilling, and a gas nozzle purging system with nitrogen as a purging gas has excellent performance and proved efficient for removing drilling cuttings. Liquid purging fluids are required for well control and other reasons, and more experimental work is required. The relative motion between laser and the sample allows better purging and lower thermal accumulation which reduce the SE and enhance penetration and ROP. Rock type has an insignificant effect on ROP in laser drilling and laser can drill soft and hard formations at approximately the same rate of penetration (ROP). Sample size affects the SE of the drilling process with large samples used to eliminate boundary effects, which is the typical case in oilfields application. Sample orientation has also a negligible effect on laser drilling, so laser application in directional drilling and oriented perforation is expected to be independent of orientation. The effect of fluid saturation is complex, and SE increases for oil-saturated samples as oil interaction with laser beams is very complex. Confining stresses and pore pressure affects laser drilling, presence of pore pressure and low confining stresses reduces SE value, while high confining stresses may increase SE because of increased rock strength. Rock interacts with the laser beam in many ways depending on the temperature of the lased point, and melting and vaporization should be avoided as possible to increase drilling efficiency. This can be achieved by carefully choosing the various laser parameters to avoid unwanted energy loss. Thermal spallation can achieve the best SE because almost all beam energy is consumed in the cutting process. Limestone and dolomite consume more energy due to decomposition interaction with laser, so higher SE are recorded for carbonates.

More experimental investigations are required to provide better understanding of the complexity in laser drilling such as the effect of liquid purging system, which is required to allow controlling formation fluids during drilling of the well. The effect of mud rheology on laser drilling needs more investigation as it can enhance purging efficiency drilling needs more investigation as it can enhance purging efficiency. The effect of saturating fluids and confining stresses also require more attention; both are critical to laser drilling and perforation. For any experimental investigation, it is recommended to use large sample sizes to avoid boundary effects and reduce the effect of variation in rock properties. Optimum parameters for laser drilling depend on each other; so, any investigation should start with optimization and detection of threshold values.

Abbreviations

BG	Brea grey
BY	Brea yellow
COIL	Chemical oxygen iodine laser
HPFL	High-power fiber laser
LS	Limestone
MIRACL	Mid-infra-red-chemical-laser
ROP	Rate of penetration
SE	Specific energy
SS	Sandstone

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Declarations

Competing interests
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