

Article

Experimental Study on Pulsed Plasma Stimulation and Matching with Simulation Work

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Abstract: Plasma stimulation is a form of waterless fracturing as it requires that only the wellbore be filled with an aqueous fluid. The technique creates multiple fractures propagating in different directions around the wellbore. The intent of this paper is to present an experimental and numerical investigation of the degree of competitiveness of plasma stimulation with hydraulic fracturing, especially in the case of stimulating tight formation. Several cases were run experimentally. The samples included limestone and sandstone to investigate plasma fracturing in different rock types. In addition, the main goal of the experiments was to study the creation of fracture(s) under confining stresses, the type of rock, the amount of electrical energy used in the experiment, and the length of the wire to generate the plasma reaction. A laboratory plasma equipment was designed and used to accomplish the experimental work. The experiments were then numerically matched using a finite element numerical simulator, HOSS developed by LANL (Los Alamos National Lab). HOSS was developed to simulate high-strain-rate fractures such as those created by plasma stimulation. It accounts for mixed-mode fracture mechanics which are tensile and shear fractures. The simulator governing equations obey the conservation of mass and momentum in a solid-mechanics sense and account for the nonlinear deformation of rock material. The matching of the experiment allowed us to validate the HOSS simulation of the process and showed that the numerical results are in good agreement with the experimental work. Using the HOSS simulator, we also investigated the effect of higher energy levels and/or short release time on a cement rock model. The pressure profile that is developed due to the energy release can vary in the peak pressure and the release time. The results showed that the plasma fracturing technique is an effective stimulation method in sandstone and limestone. Plasma fractures were developed in the rock samples and extended from the sample wellbore to the outer boundaries. The shape of the pressure pulse has an impact on the developed fractures. Moreover, the effect of plasma stimulation on natural fractures was studied numerically. It was found that natural fractures can arrest the plasma-generated fractures that propagate from the wellbore to the outer boundaries. However, new fractures may develop in the rock starting from the natural fracture tips.

Keywords: waterless stimulation; plasma fracturing; experimental study; numerical simulation



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1. Literature Review

The use of plasma fracturing was first introduced to the oil industry in 1964 to fracture various types of Colorado oil shale samples. Based on the promising results obtained from experiments, the work was then expanded to field oil shale wells [1]. Recently, many researchers have dedicated their work to electrohydraulic fracturing techniques. The technique has been investigated numerically, besides the experimental and field tests. This section presents the recent advances in electrohydraulic stimulation introduced to the petroleum literature.

Khalaf et al. [2] presented a simulation study on the pulsed fractures and a comparison to experimental work. The paper discussed the propagation of plasma features under multiple shockwaves, the effect of outer boundary conditions on the extension of the fractures, and the influence the wellbore casing has on the plasma stimulation process. They found that an efficient fracture network can be developed by an optimized sequence of repetitive shockwaves in the same wellbore. Because of the extremely high pressure generated inside the wellbore relative to the formation stresses, it has been observed that stress anisotropy has a minor impact on the propagation of the fractures. However, the value of confining stresses has a major impact on the length of the developed fractures. They reported a case where 5 MPa of stress isotropy reduced the fractures length to one-third of the length that developed under unconfined conditions.

Soliman et al. [3] presented experimental and numerical examples of plasma stimulation. They studied the effect of several parameters, including the effect of wire, input energy, confining stress, and rock type on the induced fractures. Measurement of the permeability around the plasma fractures showed that the plasma stimulation increased the rock permeability by more than one or two orders of magnitude. A numerical investigation of the effects of the stimulation technique on production was presented.

Rezaei et al. [4] reported experimental work to investigate the effect of different parameters on rock behavior under shock wave loading. The authors used purpose-built plasma discharge equipment to conduct experiments on different rock types. They observed that the energy required to create fractures increases as the confining stresses on rock samples increase. A further increase in the discharged energy generates more and longer fractures. Rezaei et al. [5] used an experimental approach to study the feasibility of plasma stimulation on permeability change. They applied single and multiple shock waves of small magnitude and imaged the rock sample with computer tomography (CT) scanning to evaluate permeability enhancement. They observed that the permeability in the region near wellbore is improved even if the discharge energy is too small to create visible cracks, and repetitive discharges creates micro-cracks that increase the permeability by up to three orders of magnitude around the wellbore and deeper inside the formation.

Safari et al. [6] used two-dimensional simulated shale cases to study the effects of in situ stresses, the peak load, rock strength level, and rock tensile strength on rock behavior. In addition, they discussed the effects of peak load and rise time on fracture geometry and wellbore integrity. Key parameters that trigger ductile/brittle transition were also studied.

Xiong et al. [7] performed experimental and numerical studies of shock wave fractures for single and repetitive loading. The results show that repetitive loading can be more effective than single loading, as it creates macroscopic, long cracks on the rock sample with less damage around wellbore. They also showed that the degraded loading mode of repetitive shocks may contribute better to crack density than upgraded loading. In addition, they developed a fitting method of the time-domain pressure/loading signal of a plasma reaction. Xiong et al. [7] conducted an experimental and numerical study to investigate the cumulative effect of cyclic loading on cement samples, showing that there are three zones created in the tested samples (crushing zone, crack zone, and elastic zone). These three zones can be controlled by adjusting the shock wave loading conditions. They proposed a methodology to minimize the crushing zone and maximize the crack zone.

Ren et al. [8,9] investigated the impact of shock waves on permeability and porosity improvement in cement and coal rock samples. They used X-ray CT scanning (North Star Imaging Inc., Rogers, MN, USA) to examine the cracks length and density in the tested specimen. Maurel et al. [10] presented experimental evaluation of permeability increase in cement samples by the application of single and multiple shock waves. Chen et al. [11] used small hollow cylindrical samples to evaluate the increase in intrinsic permeability of rock to gas by shock wave applications. They found that the energy threshold, above which an increase in permeability is observed, increases as the confining stresses on rock sample increases.

The intensity of stress loading generated by a plasma reaction can be affected by different parameters in the implementation setup. Han et al. [12], Q. Liu et al. [13], and Zhou et al. [14] investigated the use of metal fusible wires and energetic explosives in the discharge gap between electrodes to increase the intensity of a shock wave. Liu et al. [15,16] investigated the distance between electrodes to maximize the efficiency of a shock wave (transfer from electrical energy to mechanical energy), and they discussed the effect of the plasma channel length on the intensity of a shock wave. Liu et al. [17] studied the effect of the discharge modes on the peak intensity of a shock wave in water. And their work showed that the supersonic breakdown mode generates higher shock wave intensity and gives better efficiency than the subsonic mode.

Xiao et al. [18] presented laboratory work using two groups of concrete samples built under different conditions of a water–cement ratio and cased wellbore and perforation geometry. They used ionizable material in the plasma discharge to create thermite ionic reactions and reported that the use of ionizable material can increase the mechanical energy by two orders of magnitude.

Xiao et al. [19] simulated the electromagnetic fields created by the pulsed power plasma discharge using the finite element method employed in COMSOL® (Stockholm, Sweden). The work showed the agreement of the numerical work with the laboratory measurements. Analytical models of the electric current and the electromagnetic fields were developed and showed agreement with the experimental results.

Chung et al. [20] developed a numerical model to simulate the current, voltage, and pressure signals generated in a pulse plasma stimulation. The model required accurate estimations of the thermodynamic properties and electrical conductivity. In addition, the research presented a pilot test conducted on a water well for clogging cleaning. A slug test was implemented after the plasma treatment to show that the well experienced almost three times improvement in hydraulic conductivity.

Electrohydraulic stimulation has other applications in oil/gas well drilling and completion. Bazargan et al. [21] performed experimental work on plasma torch perforation and discussed its advantages over the conventional perforation techniques. The plasma torch technique can be employed to assist oil well drilling in hard formations [22]. Torch drilling mechanism is used to develop a high-temperature gradient which can modify rock properties and create fractures into the rock texture. Habibi et al. [23] used shock waves to clean a slotted liner plugged during production. Agarwal and Kudapa [24] and Alharith et al. [25] presented comprehensive reviews on the work accomplished on the plasma fracturing technique.

In this work, the development of plasma fractures in different rock types is examined. Experimental plasma fracturing work is conducted and matched with numerical simulations. The numerical work is extended to include new simulation cases.

2. Methodology

The experimental work conducted for this study was carried out using a plasma apparatus that is composed of several components. As in Figure 1, these components include two capacitors (each can store electrical energy of 10 kJ), a stainless steel cell to host the rock sample (the cell was manufactured to adapt a cubic rock model of 14 inches in size and to apply tri-axial stresses (using hydraulic pumps) to the sample in the cartesian coordinates), two oscilloscopes for recording pressure, volt and current measurements, and two electrodes that can be connected with a thin electrically conductive wire and immersed in water-filled wellbore for plasma generation. The plasma equipment is connected to a computer for monitoring the experiment and recording the data. The capacitors are connected with the electrodes that are immersed in the water-filled sample wellbore. The hydraulic pumps are connected with the cell, where the sample is accommodated for stress application. The oscilloscopes are wire-connected with the capacitors (for volt and current measurements) and the sample wellbore (for pressure measurements), and wireless-connected with a computer for data display.

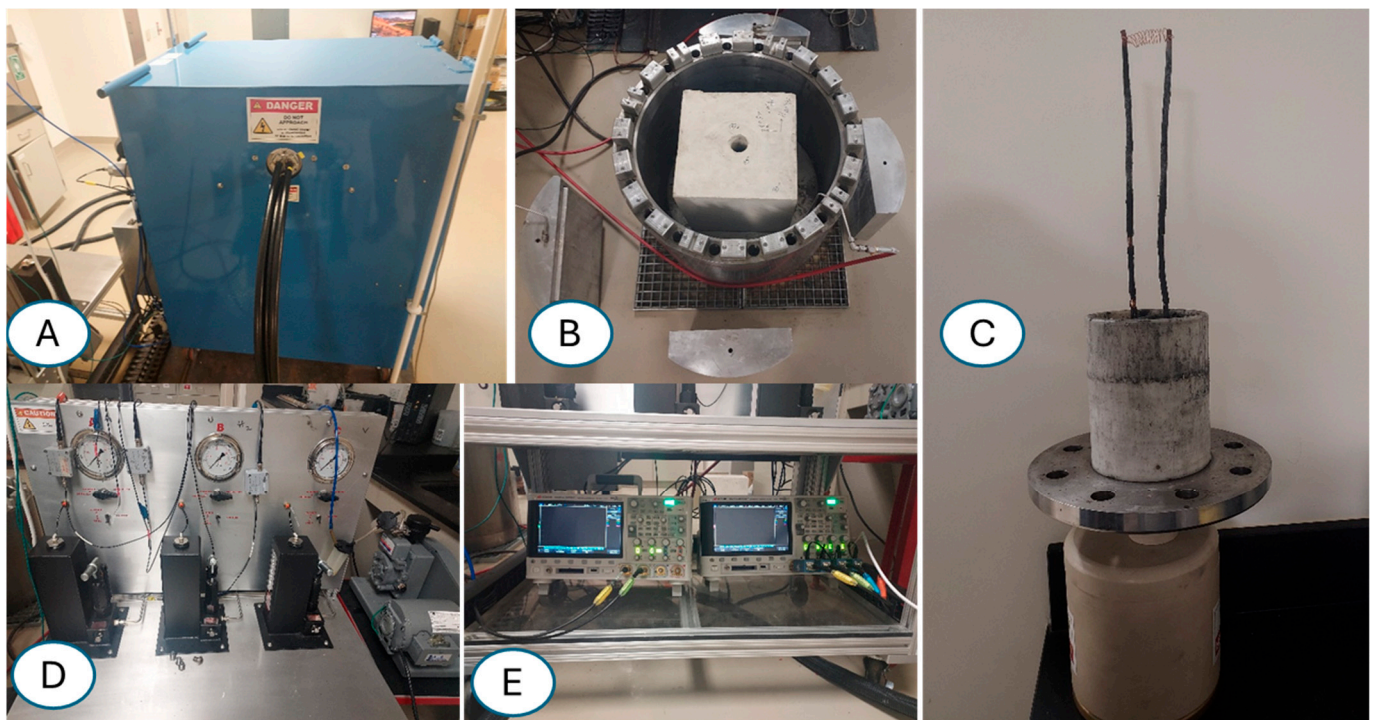


Figure 1. Plasma stimulation equipment: (A) two capacitors, (B) stainless-steel cell, (C) electrodes connected with 22-gauge Al wire, (D) hydraulic pumps, and (E) oscilloscopes.

The rock sample is fractured by pressure pulses generated with the plasma stimulation apparatus. A pressure pulse is generated when an electrical energy flows through a thin and high-resistivity wire (connects the two electrodes) immersed in a water-filled wellbore. This results in a plasma reaction that develops the pressure pulse. The technique relies on a release of the electrical energy stored in the capacitors through a thin conductive wire that connects the two electrodes. The two electrodes are immersed inside a conductive electrolyte (water) filling the sample wellbore. The sudden release of the electrical current allows the wire to burn, and plasma reaction occurs and develops a pressure pulse that propagates fractures in the rock sample.

For the simulation work carried out in this study, the hybrid multi-physics software package HOSS[®] (Hybrid Optimization Software Suite <https://www.lanl.gov/orgs/ees/hoss/index.shtml> accessed on 1 January 2024) is used to perform the calculations. The model is assumed to be non-porous and does not account for fluid flow. The assumptions are reasonable as the plasma stimulation technique develops fractures within a microsecond timescale that does not give a chance for the fluid to affect the fractures development. The package is developed to model high-strain-rate cases, such as fractures developed by plasma pressure pulse inside wellbore of rock sample. HOSS[®] uses the finite-discrete element method that combines the finite element method and discrete element method and assumes a continuous rock body. The fractures developed in the rock model propagate when the failure model is met. The general equation controls the system is solved in the finite-discrete element method and follows the conservation of mass and momentum in a solid-mechanics way and is presented as [26,27]

$$M\ddot{x} + C\dot{x} = f \quad (1)$$

where M is lumped mass matrix, C is damping matrix, x is displacement vector, and f is equivalent force vector acting on each node. The integration of Equation (1) with respect to time gives the transient changes of the model over time.

The element interfaces of the finite elements used as a numerical method for solving the system-governing equations are connected by non-linear springs. However, the finite

elements that construct the rock model can be deformed in the form of translation, rotation, and stretch. The springs that attach the element interfaces behave according to the non-linear stress–strain curve shown in Figure 2. The curve is composed of strain-hardening part and strain-softening part. In the strain-hardening region, the rock follows the elastic behavior until it hits the rock failure point. In this region, no fractures grow and the constitutive law is employed along with the plasticity (non-linearity). However, as the rock exceeds the failure stress in the strain-softening region, fractures develop and the constitutive law states the evolution of stresses at the interfaces as a function of the relative displacement (developed fractures) [28].

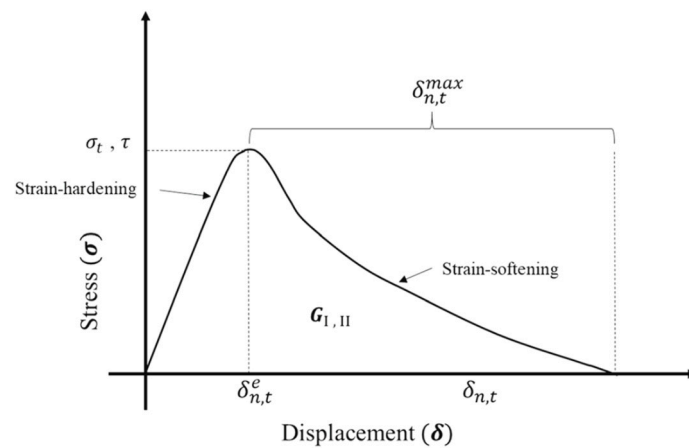


Figure 2. Schematic of the stress–strain curve used in HOSS [29].

As the fractures develop in the strain-softening part of the stress–strain curve (Figure 2), the calculations account for a mixed mode fracture propagation and two types of fractures can develop: tensile and shear. The tensile fractures are developed when the normal displacement (δ_n) developed between two elements reaches the normal displacement (δ_n^e) corresponding to the rock tensile strength (σ_t). However, the shear fractures are generated when the elements shear displacement (δ_t) reaches the shear displacement (δ_t^e) corresponding to the rock shear strength (τ), as given by Mohr–Coulomb model, shown in Figure 3 [29]:

$$\tau = c + \sigma_n \tan(\phi) \quad (2)$$

where c is internal cohesion, σ_n is normal stress, and ϕ is angle of friction.

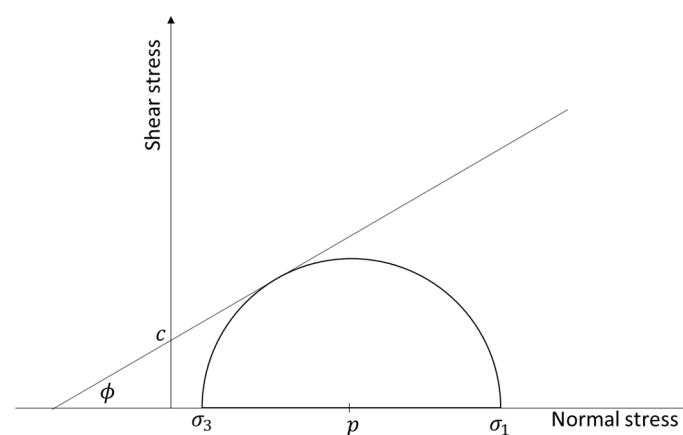


Figure 3. Schematic illustration of Mohr–Coulomb failure criterion.

3. Results and Analysis

This section presents four experiments and the relevant simulation work. The four rock samples are two sandstone samples and two limestone samples. Each rock type is examined under confined and unconfined stress conditions. HOSS[®] is used in simulation work to match the experimental work. This section discusses additional cases of fracturing using a nano-second pressure pulse and naturally fractured rock cases.

3.1. Sandstone Sample 1

A cubic sandstone sample with dimensions of 14 inches is used for plasma stimulation. The sample has a vertical wellbore that is 10-inches in length and 2-inches in diameter. The sample outer boundaries are subjected to unconfined conditions and exposed to atmospheric pressure. The wire used for the plasma reaction is Aluminum (Al) of a 22-gauge size. Five inches of wire is used to connect the two electrodes immersed in the sample wellbore that is filled with water. The electrical energy used for the generation of the plasma reaction is 6 kJ.

The sandstone sample was subjected to two identical plasma pressure pulses. The release of the first pulse was sufficient to develop one narrow fracture that extended along one side of the sample, as shown in Figure 4. However, by releasing the second pressure pulse inside the rock wellbore, the fracture generated by the first shot was further widened and a new wide fracture was created on the other side of the sample. The final shape of the fracture is a two-wing fracture that extends from one side of the sample to the other passing through the wellbore as shown in Figure 5 (the two sides of the sample are shown in the figure).



Figure 4. Plasma-propagated fractures using first pressure pulse—unconfined sandstone sample.



Figure 5. Plasma-propagated fractures after second shot—unconfined sandstone sample.

The experimental work is simulated numerically using HOSS[®]. The pressure pulse generated from the plasma reaction is given in Figure 6. The pressure ramps exponentially to reach a peak value of 50 MPa and then declines exponentially to reach atmospheric pressure at 60 μ s. The pressure profile used in this study was developed based on experimental observations by Xiong et al. [30] and employed in a study by Khalaf et al. [2]. A cubic rock model with a circular wellbore is generated and meshed using Cubit[®]. The model's outer boundaries are kept free to move during the pulse application. The inner boundary of the rock model (wellbore) is subjected to the pressure profile. The sandstone properties are listed in Table 1.

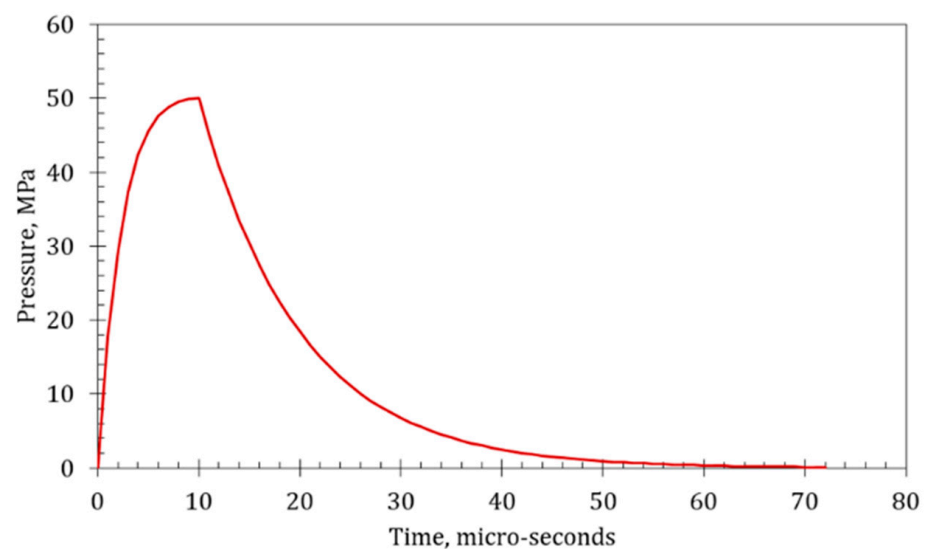
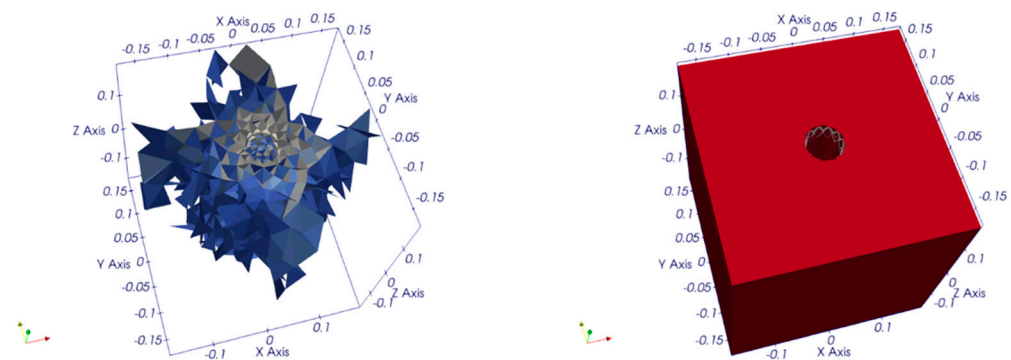
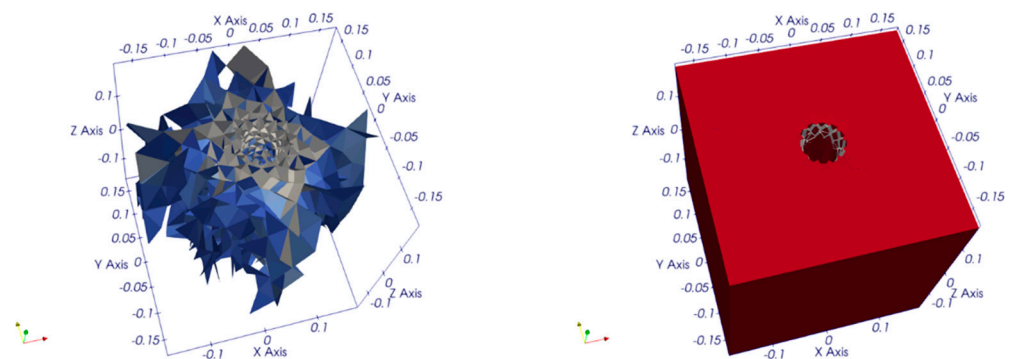


Figure 6. Pressure pulse profile developed by plasma stimulation.

Table 1. Mechanical properties of sandstone for simulation.

Property	Value	Unit
Poisson's ratio	0.24	
Young's modulus	12.1	GPa
Friction angle	41.5	Degrees
Tensile strength	2.5	MPa
Shear strength	1.25	MPa
Density	2600	kg/m ³

The application of the first pressure pulse results in the fractures shown in Figure 7. In the figure, there are two graphs. The left graph shows the fractures only (separation between the finite elements). The blue color is for narrow fractures and the gray is for wide fractures. However, the graph to the right shows the whole model including the fractures. The intact rock is red, and the fractures are light gray. When a second pulse was applied to the same fractured sample, the old fractures widened and extended to the model boundaries, as given in Figure 8. The figures show the separations that represent the fractures between the model finite elements to the left, and the whole model to the right.

**Figure 7.** Fracture development by applying first pulse: fracture element (**left**) and fracture sample (**right**).**Figure 8.** Fracture development by applying second pulse: fracture element (**left**) and fracture sample (**right**).

3.2. Sandstone Sample 2

A sandstone sample was used to study plasma fracturing under confining stresses. The dimensions of the rock sample are the same as the unconfined case, which are 14-inches for the cube side length, 2-inches for the wellbore diameter, and 10-inches for the wellbore height. The vertical confining stress is 3 MPa, and the horizontal stress values are 2.7 MPa and 2.4 MPa. The wire used between the electrodes is Al of 22 gauge.

Four plasma pulses were released inside the sample wellbore. The results showed that the confined sandstone sample was intact after the first three pressure pulses. The first

two pulses used 9 kJ electrical energy and a 20-inch wire length. In the third pulse, the energy increased to 10 kJ and the wire length was 20-inches-long. The energy released for the fourth pulse was 10 kJ and the wire length was 25-inches. The fourth pressure pulse was able to develop minor fractures in the rock as given in Figure 9.

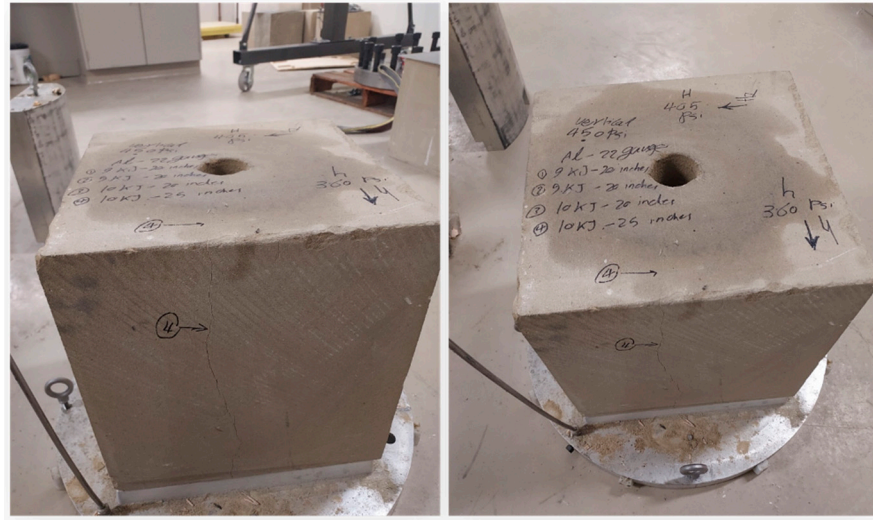


Figure 9. Confined sandstone sample.

A numerical model was created to simulate the confined sandstone experiment. The sandstone properties listed in Table 1 are used in the numerical simulation. Since the energy and the wire length used in the confined sandstone experiment are higher than those of the unconfined case, a higher pressure pulse is used. The peak values of the four pressure pulses applied to the confined case are 60, 60, 65, and 70 MPa in order. The pressure pulse profiles are given in Figure 10.

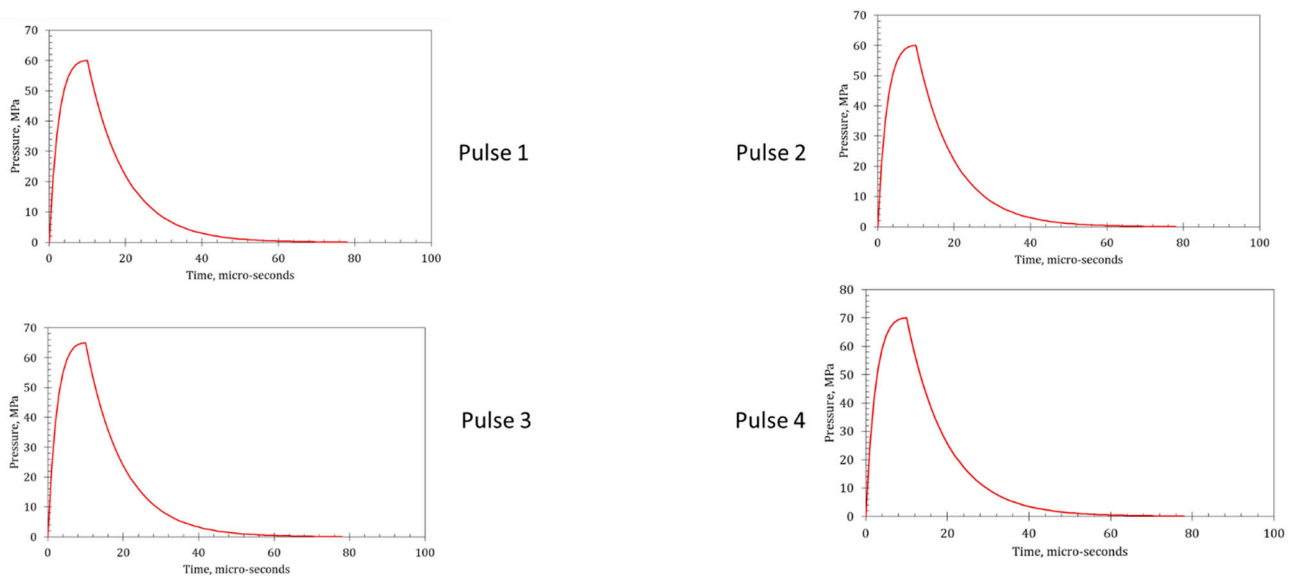


Figure 10. Pressure pulses of the confined sandstone sample. The peak pressure is 60 MPa in the first two pulses, 65 MPa in the third pulse, and 70 MPa in the fourth pulse.

The four pressure profiles are applied in succession to the model wellbore. The numerical model was intact after the application of the first pressure pulse. However, the sample experienced fractures in the following three pulses. The results from the last three pulses are given in Figures 11–13. The fractures developed in the second and third pulses

are minor and can be interpreted as an improvement in permeability, as shown in Figures 11 and 12. The results show agreement between the experimental and the simulation work, where the fractures propagate all the way to the sample edges.



Figure 11. Fractured sample—second pressure profile.

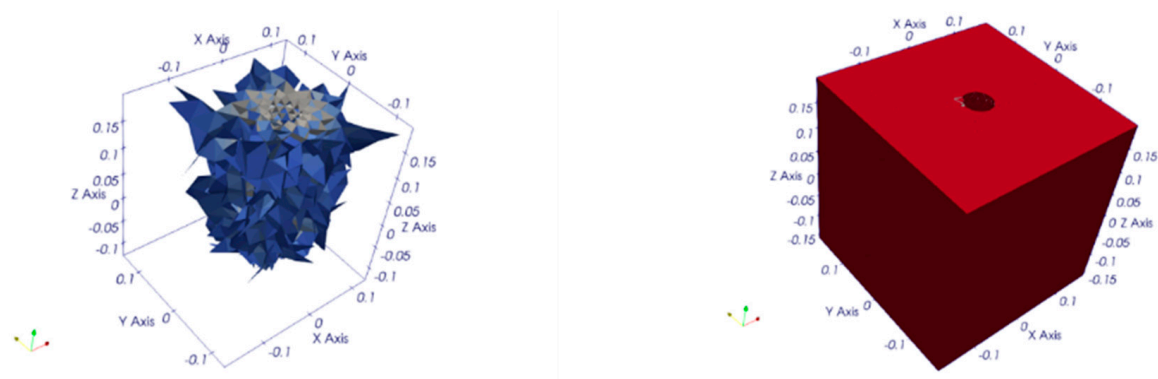


Figure 12. Fractured sample—third pressure profile.

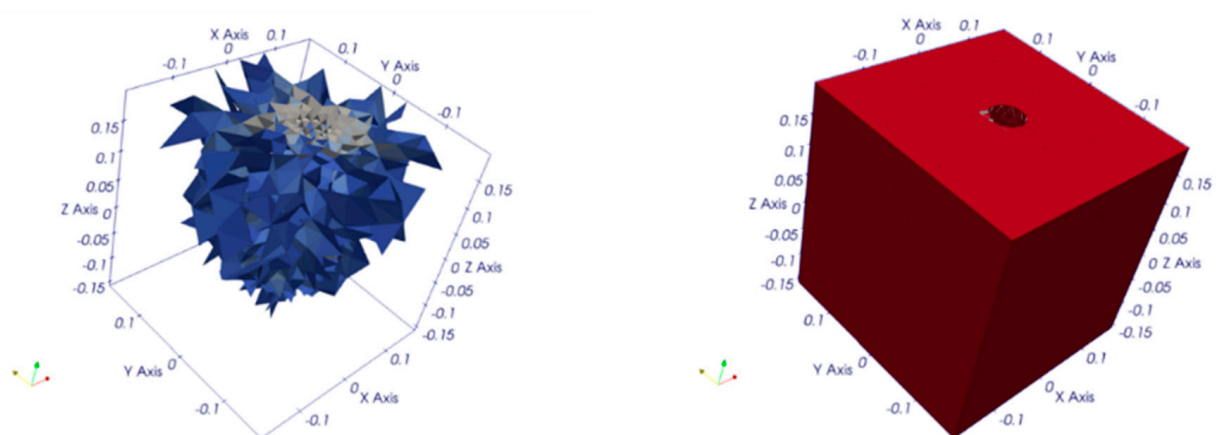


Figure 13. Fractured sample—fourth pressure profile.

3.3. Limestone Sample 1

The cubic limestone sample has a side of 14 inches and a vertical wellbore, 2 inches in diameter and 10 inches in height. The sample is unconfined, and the experimental run parameters are 6 kJ energy and 5-inch 22-gauge coiled Al wire. The application of the plasma pulse caused the sample to crack, and fractures were developed, as illustrated in Figure 14. Two fractures propagated on one side of the sample and a third fine fracture grew on the other side of the sample.



Figure 14. Fractured limestone sample: top view to the left and side view to the right—unconfined case.

The experimental limestone fracturing process was simulated using HOSS[®]. The material properties of limestone were taken as given in Table 2. A 14-inch cubic model with a circular wellbore that is 2-inches in diameter and 10-inch height was created. In Figure 15, a pressure profile of 50 MPa peak pressure was used to mimic the pulse generated by the 6 kJ and 5-inch wire. The pressure pulse was applied inside the model wellbore, while the outer sides were kept unconfined (free to move during the application of pressure pulse). The pressure pulse application resulted in the fractures shown in Figure 16. The figure shows that multiple fractures developed to match the experimental results given in Figure 14.

Table 2. Properties of limestone sample.

Property	Value	Unit
Density	2700	kg/m ³
Young's modulus	20	GPa
Poisson's ratio	0.27	
Friction coefficient	0.6	
Tensile strength	2	MPa
Shear strength	1	MPa

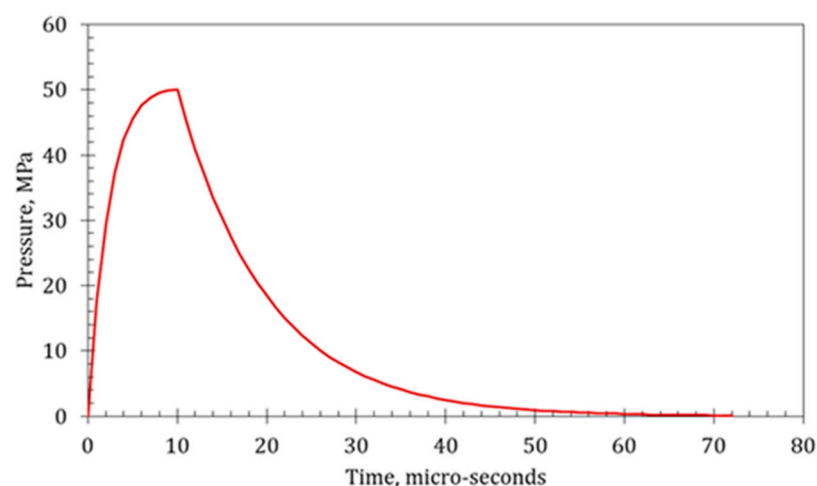


Figure 15. Pressure pulse for unconfined limestone sample.

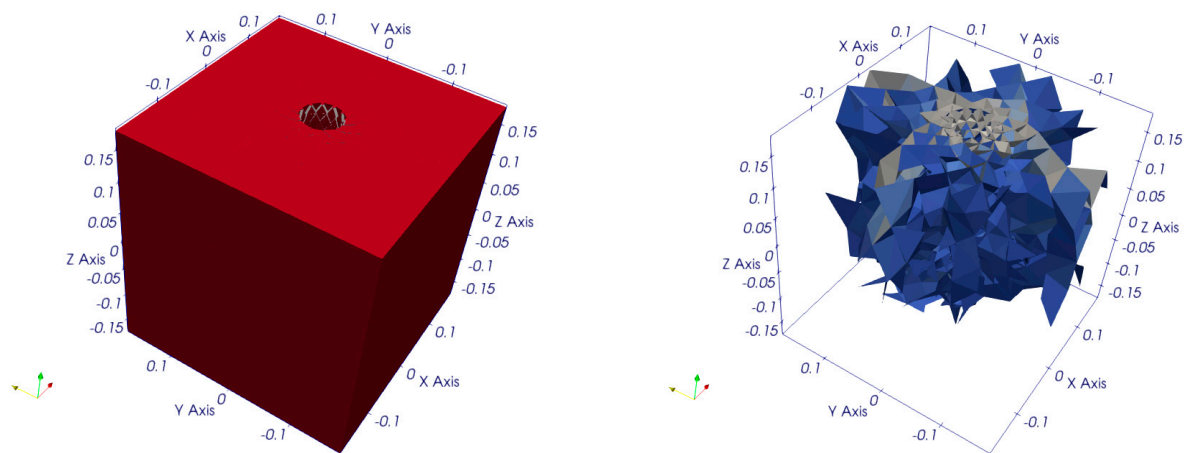


Figure 16. Simulation results of unconfined limestone experiment: fractured model (left) and developed fractures (right).

3.4. Confined Limestone Sample

This section studies the effectiveness of the plasma stimulation technique in the confined limestone formations. A cubic limestone sample has the dimensions of a 14-inch side length and a 2-inch wellbore diameter was subjected to confining stresses. The sample was placed inside the tri-axial plasma cell and stresses of 360, 405, and 450 psi were applied in the two horizontal directions and the vertical direction, respectively.

After the relaxation of the sample under stresses, a sequence of pressure pulses was released inside the wellbore and the sample integrity was examined after each pulse release. The first two plasma pulses were generated using 20-inch Al wire of 22 gauge and energies of 9 kJ. These plasma specifications are the same as those of the confined sandstone experiment presented in this study. Checking the confined limestone sample after each pulse showed that the rock was intact, and the pulses did not grow fractures in the limestone. A third plasma reaction was generated inside the sample wellbore using 20-inch Al wire and 10 kJ electrical energy. The current and volt measurements recorded by the oscilloscopes are shown in Figure 17. The time duration of the pressure pulse applied to the simulation model is taken from the volt and current data measurements. In the third pulse, the limestone developed fractures that propagated from the wellbore towards the sample edges. The results are shown in Figure 18. In the figure, three fractures are developed from the wellbore. One of the fractures grew and reached the outer edge of the sample. However, the other two fractures propagated, to a certain extent, almost half the distance from the wellbore to the edge.



Figure 17. Volt (yellow) and current (green) waveforms of plasma generated in the confined limestone sample.



Figure 18. Confined limestone sample after the third plasma pulse.

The confined limestone experiment was simulated numerically. A cubic model of the same dimensions as those of the rock sample was built. The simulation process was carried out in two stages. In the first stage, the outer boundaries of the created model were subjected to confining stresses (360, 405 and 450 psi in the three directions) and allowed to relax under the confining stresses. The sudden application of the confining stresses to the outer boundaries generated kinetic energy (vibrations) in the rock. During the relaxation stage, the model was brought to the static state (zero kinetic energy) before the fracturing stage [2]. During this relaxation stage, the inner boundary conditions in the wellbore were atmospheric pressure. In the second stage, the pressure pulses were released inside the wellbore while keeping the outer boundaries subjected to confinement. A similar sequence of pressure pulses to the confined sandstone model was applied to the confined limestone model, and the first two pulses were equivalent to 60 MPa pressure peak. The peak pressure was then raised to 65 MPa in the third pulse. The application of the first 60 MPa pressure pulse did not introduce fractures into the model. The second pulse of 60 MPa pressure was introduced and was able to develop minor fractures around the wellbore, as demonstrated in Figure 19. The third pressure pulse of 65 MPa pressure extended these fractures to reach the model outer boundaries, as given in Figure 20.

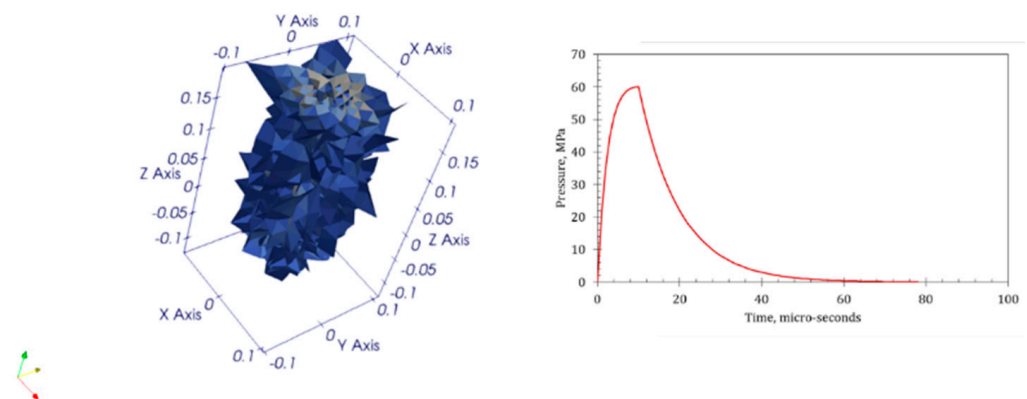


Figure 19. The developed fractures (left) and the pressure pulse (right)—second pulse.

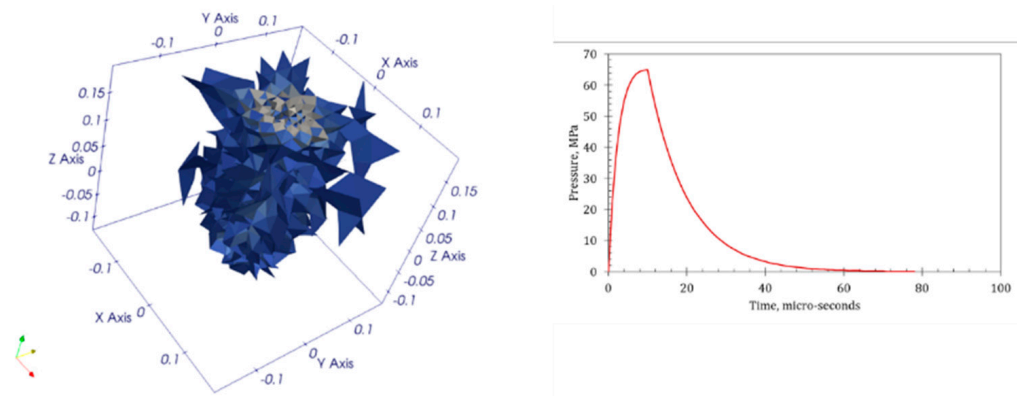


Figure 20. The developed fractures (left) and the pressure pulse (right)—third pulse.

3.5. Natural Fractured Rock Simulation

The numerical rock model developed here is used to simulate naturally fractured rock. The 2-D square model dimensions are 2 m side length and 10 cm wellbore diameter. The natural fractures in the rock are simulated as material inclusions of different properties from the rock matrix. Three fractures are introduced into the rock model and each natural fracture has a length of 1 m and a width of 1 mm, as given in Figure 21. The matrix properties along with the properties of natural fractures are listed in Table 3.

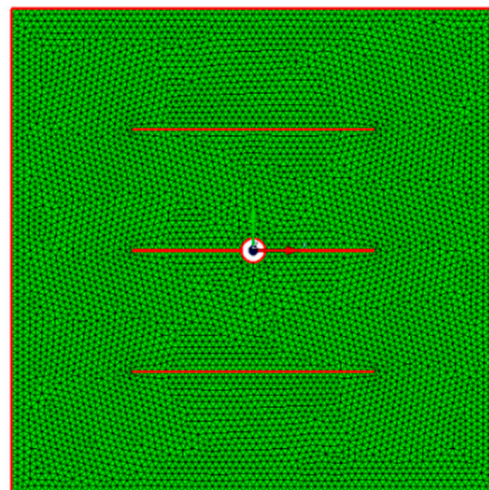


Figure 21. Squared rock model with three natural fractures.

Table 3. Material properties of matrix and natural fractures.

Property	Matrix Value	Natural Fracture Value	Unit
Density	2700	2500	kg/m ³
Young's modulus	30	10	GPa
Poisson's ratio	0.27	0.35	
Friction factor	0.6	0.5	
Shear strength	10	2.5	MPa
Tensile strength	2	0.5	MPa

A pressure profile of 100 MPa peak is applied to the model wellbore to simulate plasma stimulation pulse. The pressure increases exponentially to reach its peak and then decreases exponentially to one atmospheric pressure, as in Figure 22. The sample outer sides are subjected to free boundary conditions. The application of the pressure profile results in the fractures shown in Figure 23. A threshold is used to develop the results graphs after the

fracturing process. The threshold used here is of a value of 0.5. The fractures developed in the rock can be scaled from 0 to 1. The zero value means that no fractures are propagated, and the rock is intact. However, the value of one means that the rock is fractured, and the fracture is completely open (the finite elements are fully separated).

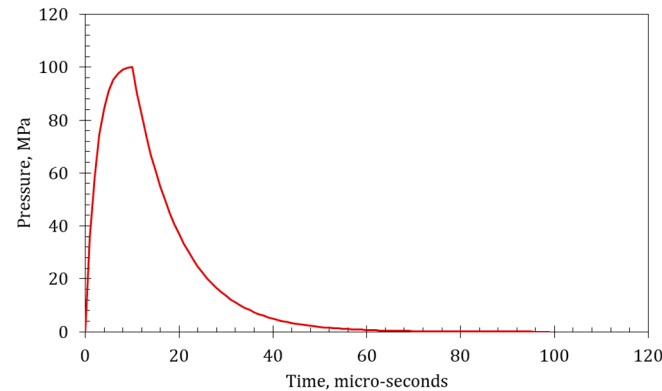


Figure 22. Pressure pulse used for the natural fractured rock.

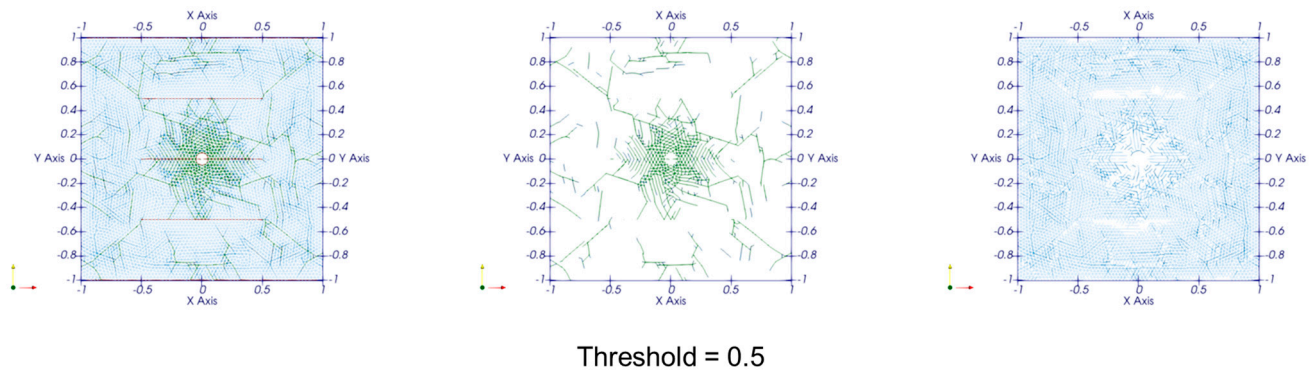


Figure 23. Fractures developed in naturally fractured rock: all fractures (**left**), major fractures (**middle**), and minor fractures (**right**). Fractures are green (major) and greenish blue (minor), intact rock is in light blue, and natural fractures are in red.

In Figure 23, the first graph to the left shows the sample after fracturing, where all fractures are depicted. In the middle, the major fractures of a width greater than the 0.5 threshold are illustrated. However, the minor fractures that represent improvements in permeability are shown in the figure to the right. The threshold is a value used in result visualization, where the width of the developed fractures is normalized between zero and one. Zero means that the rock is intact and one is for a fully open fracture. The results in Figure 23 show that the plasma stimulation pulse affects the whole model. Major fractures (shown in the middle graph) propagate from the wellbore and reach the model's outer boundaries. One also can observe that the natural fractures arrest the plasma-developed fractures. However, new plasma fractures grow from the tips of the natural fractures. Moreover, the plasma stimulation method develops minor fractures in the rest of the rock model as shown in the graph to the right. These minor fractures are interpreted as enhancement in the rock permeability. The improvement in permeability obtained by plasma stimulation is verified experimentally by Soliman et al. [3].

The main fractures (wider than a specific threshold) are given in Figure 24 for different thresholds, where 0.5, 0.7, 0.9, and 1 are shown. The threshold of one shows the fractures that are completely opened, where the elements are completely separated. In the results, on the one hand, one can observe that the pulse fractures propagate from the wellbore toward the boundaries. The presence of the natural fractures restricts the fracture growth to the boundaries, where the natural fractures arrest the pulsed fractures. However, on the

other hand, pulsed fractures start to propagate from the tip of natural fractures toward the outer boundaries.

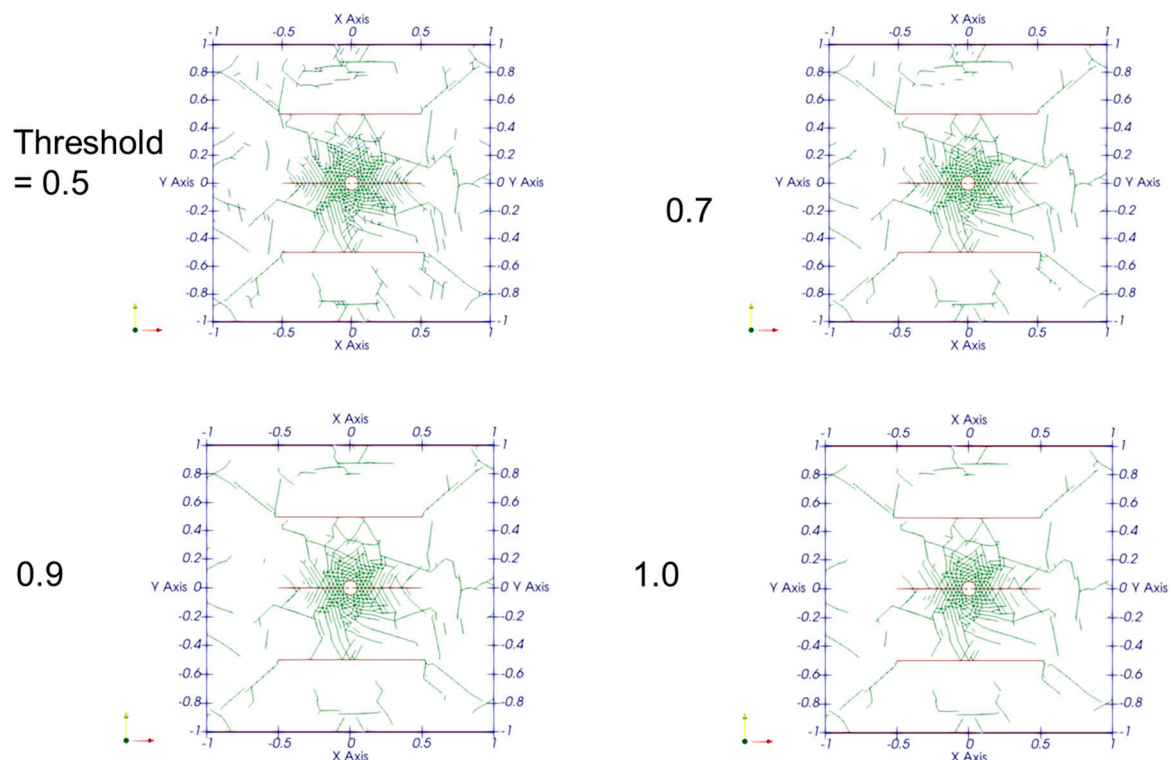


Figure 24. Major fractures of different thresholds developed in the naturally fractured model.

3.6. Nanosecond Pressure Profile

This section investigates the effect of the nanosecond pressure pulse profile on fracture propagation in a cement rock model. A 2D numerical circular model was created of outer diameter of 6 ft (182.88 cm) and a wellbore radius of 3 inches (7.62 cm). The outer boundary conditions of the model are unconfined. The model properties are taken for cement as listed in Table 4.

Table 4. Cement properties for nanosecond pressure pulse study (Goldgruber and Lampert [31]).

Property	Value	Unit
Young's modulus	33	GPa
Poisson's ratio	0.25	
Density	2300	kg/m ³
Tensile strength	2.9	MPa
Shear strength	1.45	MPa
Friction factor	0.6	

Three pressure pulses are applied to the model wellbore. These three cases are selected to examine the effects of the shape of the pressure profile (the pressure peak value and the time extension). In the first case, a pressure pulse of a 2000 MPa peak and a 50- nanoseconds time extent are applied inside the circular wellbore. The pressure ramps exponentially and decays exponentially until it reaches atmospheric pressure. The application of the pulse does not develop fractures in the cement rock model, as shown in Figure 25. The peak of the pressure pulse was increased to high, unrealistic values. However, the fractures that were developed in the model were minor and not adequate for a successful pulse fracturing process.

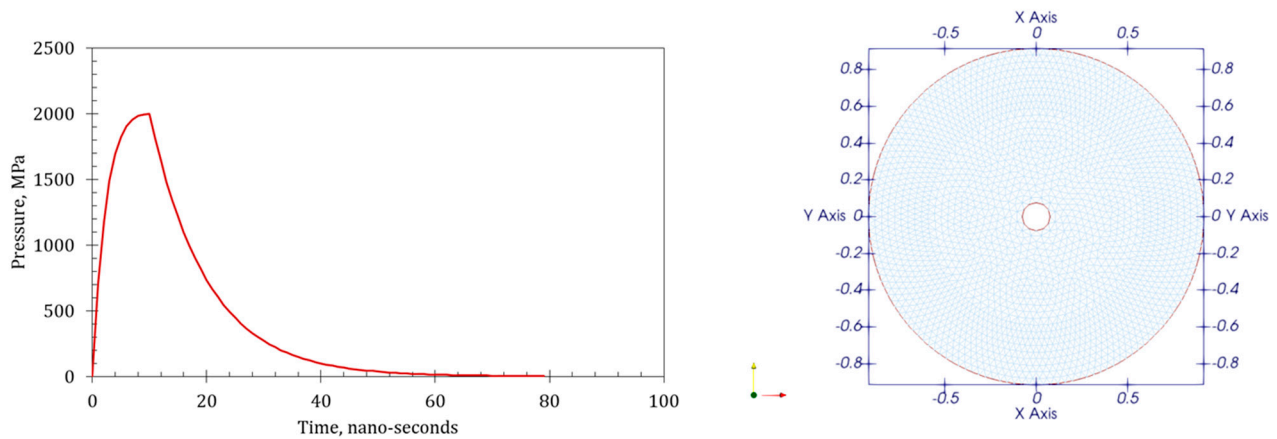


Figure 25. Pressure pulse (left) and results (right) of the nanosecond pressure profile—case 1.

4. Conclusions

In this study, experimental and numerical work on the plasma stimulation technique is presented. Four rock samples are employed to study plasma stimulation under confined and unconfined rock conditions. Moreover, numerical study is presented to investigate the effect of plasma fracturing on natural fractures and to examine the plasma stimulation using nano-second pressure pulses. The results show the following:

1. Stimulating confined rock using the plasma technique requires more energy and repetitive pulses to fracture than the unconfined case of the same rock type. It is noticed that fracturing the confined sandstone sample took four plasma pulses of more energy than the unconfined sandstone which was cracked after one pulse of less energy.
2. The rock type affects the development of plasma fractures. The confined sandstone sample required the release of plasma energy four times. However, the confined limestone sample was fractured after three pulses. This may be attributed to the rock tensile strength that is higher in sandstone than limestone.
3. The natural fractures numerical case shows that the presence of natural fractures can arrest the propagation of the plasma fractures. However, new plasma fractures may propagate from the natural fracture tips.
4. The extension of the plasma pressure pulse on the time axis has a greater effect on the developed fractures than the value of the peak pressure.

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