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Optimizing Perforating Charge Design for Stimulation

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Abstract

Hydraulic stimulation technologies, which are vital in maximizing the production of unconventional reservoirs, have typically focused on pumping capacities and rates, hydraulic fluid viscosities, and proppant materials. A technology that historically has been overlooked, but is critical to an efficient hydraulic stimulation, is the actual perforations through which the treatment is pumped.

Fundamental rock and fracture mechanics demonstrate that perforation shot density, phasing, and hole size affect breakdown and treating pressures and injection rates, and can be a cause of early screenout. Although some of these perforation parameters are considered in the best practices, perforation hole size is often misunderstood.

Complex computer fracture models, used to plan stimulation and completion programs, often incorporate average hole-diameter values with little consideration of the actual hole sizes or the variance from shot to shot. New research documents how this inconsistency can be considerable when using standard shaped-charge perforators. Nevertheless, perforating charges designed for natural completions, which focus primarily on the depth of penetration, are continuously used before hydraulic stimulation, ignoring the importance of consistent hole size. Advanced simulations using finite element analysis (FEA) have confirmed that fracture placement in a reservoir requiring stimulation would benefit significantly from maintaining consistency in the size of the perforation exit-hole.

This work reviews the analysis performed and the subsequent successful field results for a new class of shaped-charge. The new fracture charge is engineered to maximize hole-diameter while maintaining a consistent exit-hole diameter independent of well profile and/or gun eccentricity. Designed for perforating before a hydraulic stimulation, a fracture charge has been shown to optimize fracturing efficiency and placement by ensuring that each perforation tunnel contributes equally during the fracture treatment, which contributes to providing cost effective hydraulic stimulation and maximizing subsequent asset value.

Introduction

Before any stimulation of a cased well completion, a conductive path must be established from the wellbore into the target reservoir rock. Several technologies currently exist, such as sliding sleeves, to create this conduit; however, the most popular technology is perforating because of its overall efficiency, reliability, and historically successful track record. Perforating oil and gas wells using specially designed shaped charge jet perforators has been used extensively since its introduction in the late 1940s. Broad improvements have been applied in the design and materials used since this process was first introduced as the physics have become better understood and testing techniques have advanced and evolved. Shaped charges can now be designed and manufactured for specific applications and conditions, enabling deeper penetration, maximum or minimum casing-hole diameter, and/or the ability to penetrate through only selected tubing or casing strings without penetrating the outer string. However, with all of the advances in perforator design and technology, no shaped charge had been developed to minimize the variation in perforated casing-hole size until now. In addition, stimulation treatment designs have not considered that variation does exist and that it is typically dependent upon gun-to-casing clearance.

Fracture stimulation has demonstrated great success in conventional reservoirs where it was common to focus solely on completing a single zone for production. However, with the industry continuing to trend toward unconventional and resource type plays, which have much lower permeability and larger gross intervals than traditional conventional reservoirs, the focus has shifted to completion methods that can effectively implement multiple stimulation treatments conducted consecutively to maximize efficiency and minimize time to production.

It has been shown that, in horizontal wells drilled in unconventional reservoirs, the degree of stimulated reservoir volume (SRV) is directly proportional to the resulting production (Mayerhofer et al. 2008). It has been shown that SRV can be improved by increasing the number of stimulation points along the horizontal wellbore. This concept can also be applied to vertical wells that are drilled through long intervals of potentially productive stacked sands, silt, shale, and carbonates.

Although there are several viable completion methods applicable to stimulating long intervals in vertical wells, the method using limited entry perforating (LEP) (Lagrone and Rasmussen 1963) is optimal for stimulating multiple intervals simultaneously to achieve a high SRV in a timely and cost effective manner. The LEP stimulation design uses standard hydraulic equations to define the pressure decrease across the perforations and the pressure decreases that occur between the perforations as a function of hydrostatic and friction pressure. In addition to these pressure decreases, full consideration of the fracturing pressure at each perforation point must be made. The objective of these calculations is to determine the size and number of perforations required at each stimulation point to distribute the stimulation fluid evenly across the intended interval, as shown in **Fig. 1**.

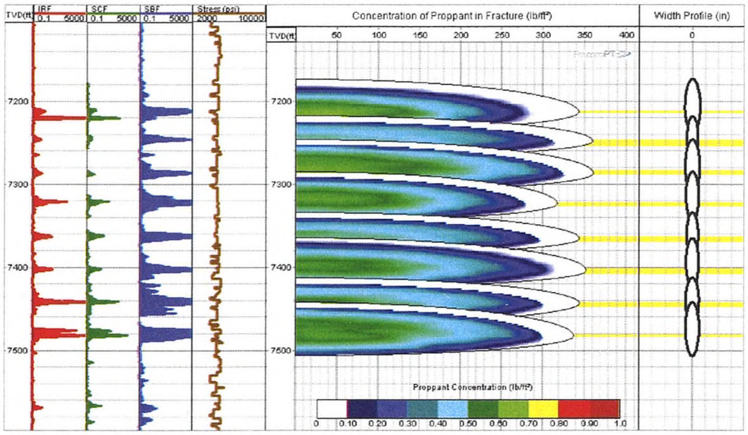

Fig. 1—LEP design concept creating eight fractures simultaneously. Post-fracture tracer profile (left) validates the design concept.

In practice, one of the main obstacles to LEP design is the inherent circumferential inconsistency in the diameter of the perforations when using standard perforating charges without centralization. Because the stimulation fluid must divide and pass through several perforations and then recombine before flowing down the fracture plane, any variation in the circumferential perforation size can disrupt the fluid convergence, which results in greater than expected injection pressures and possible bridging of the propping agent. This behavior is often referred to as near-wellbore tortuosity (Romero et al. 1995), as shown in Fig. 2

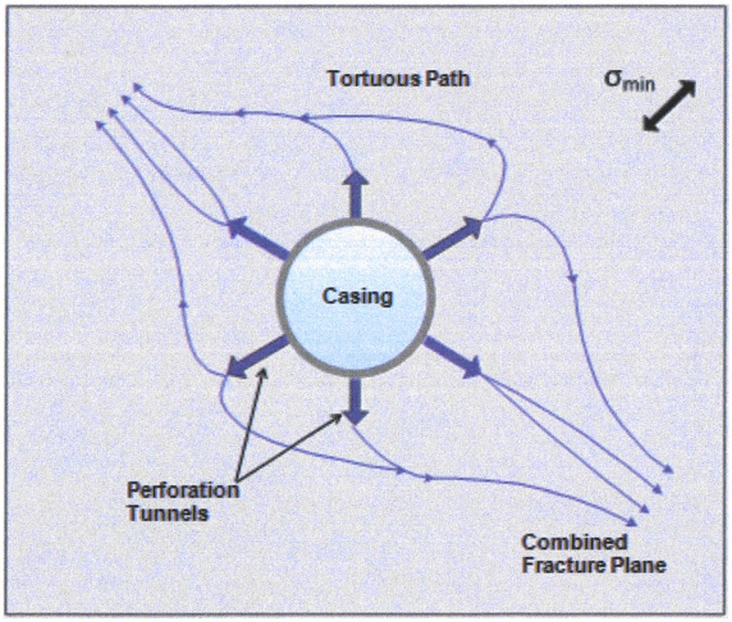

Fig. 2—The concept of flow convergence between perforation tunnels and tortuosity.

In several ongoing multiple well resource play projects, high injection pressures and bridging of the propping agent frequently occurred during the stimulation. An analysis of the injection pressures led to the premise that the standard perforating charges were not optimal and that a high degree of tortuosity existed. Treatment fluids were believed to be contributing through only some of the perforations because of the known inconsistent perforation diameter circumferentially around the wellbore caused from variations in gun-to-casing wall clearance. This casing-hole variation was assumed to cause a high degree of near-wellbore tortuosity. To test this premise, an existing perforating charge with a shallower penetration and a more consistent hole diameter than the previous charge was used; a moderate reduction of injection pressure and a reduction in the frequency of bridging of the propping agent was observed. This observation led to the research, design, and development of a new optimized perforating shaped charge tailored for perforating before stimulation treatment begins.

Fracture Physics – Casing Hole Size and Orientation

We have developed a simplified model to preliminarily investigate the role of perforation tunnel geometry during the hydraulic fracturing process. In particular, because of the known effect of gun-to-casing clearance and the challenges observed while treating wells, the focus was placed on the consistency of the casing entrance-hole diameter in affecting fracture initiation. The model incorporates a finite element stress analysis with a fracture initiation criterion. The finite element analysis has been performed using the commercial software ABAQUS/Standard (2011) to determine the stress distribution around the perforating tunnel. The model developed establishes the connection between the breakdown pressure and the local stresses along the surface of the perforation tunnel.

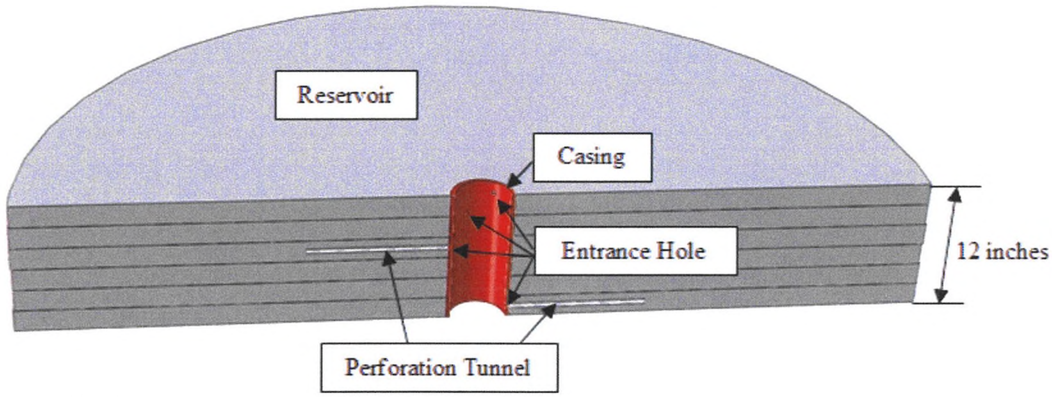

Fig. 3—The model geometry.

As shown in **Fig. 3** (only half of the model is shown), the simplified model consists of the steel casing with six holes over a 12-in. interval and the reservoir. Each casing-hole is treated as a cylindrical hole. Corresponding to each casing hole, a cylindrical perforation tunnel is created with the length of 15 in. and the same diameter as that of the casing-hole. The reservoir model height is equal to the perforated interval of 12 in. and a radius of 50 in. Additional study indicated that the reservoir in the present model is sufficiently large such that the stress distribution near the perforation tunnel and the casing does not depend on the reservoir boundary. **Fig. 4a** shows the mesh configuration of the reservoir model; **Fig. 4b** provides a close view of the region near the perforating tunnel. The mesh is refined in the region near the perforation tunnel. For simplification, both the reservoir rock and the steel casing are considered as linear elastic materials. A uniformly distributed pressure, p, (=100 MPa) is applied to both the surface of the perforating tunnel and the casing.

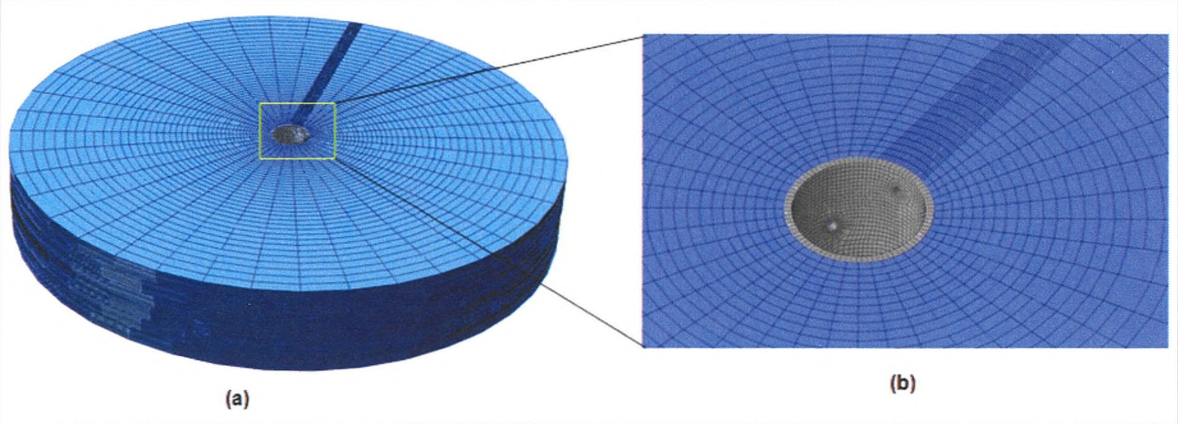

Fig. 4—Finite element mesh configurations.

In this study, the entrance-hole diameters of the six perforation tunnels were varied, but the influence of the tunnel length and irregularities of the geometry of the real perforation tunnel has not been explored. Three cases are considered: (1) an ideal case in which all six tunnels have the same entrance-hole diameter; (2) a specific case in which the entrance-hole diameters vary from 0.36 to 0.48 in., as a representative having less variation in the perforation entrance-hole diameters (EHD) created by a specially designed shaped charge; (3) a specific case in which the entrance-hole diameters vary from 0.25 to 0.55 in., as a representative having larger variation in the perforation EHD created by a conventional deep penetration shaped charge. As testing has confirmed and will be presented later in this work, the perforation EHD varies relative to the clearance between the perforating gun and the casing wall.

Fig. 5 shows the numerically predicted distribution of the local maximum principal stress (MPS) on the surfaces of the perforation tunnels and the wellbore. In the figures, red indicates a large magnitude of the stress, and blue indicates a relatively small magnitude. For all three cases, the local maximum principal stress (MPS) is always on the top surface of the perforation tunnel near the base of the perforation and near the wellbore surface. This outcome is consistent with the previous work completed by Behrman and Elbel (1991). The entrance-hole diameter greatly contributes to fracture initiation, whereas the tunnel length has a much smaller effect on the initial perforation breakdown.

TABLE 1—SUMMARY OF FEA RESULTS COMPARING EHD TO MPS

Scenario	Entrance-Hole Diameter		Maximum Principal Stress	
	Minimum	Maximum	Minimum	Maximum
Case 1	0.43 in.		152.7 MPa	
Case 2	0.36 in.	0.48 in.	149.9 MPa	157.2 MPa
Case 3	0.25 in.	0.55 in.	144.8 MPa	162.5 MPa

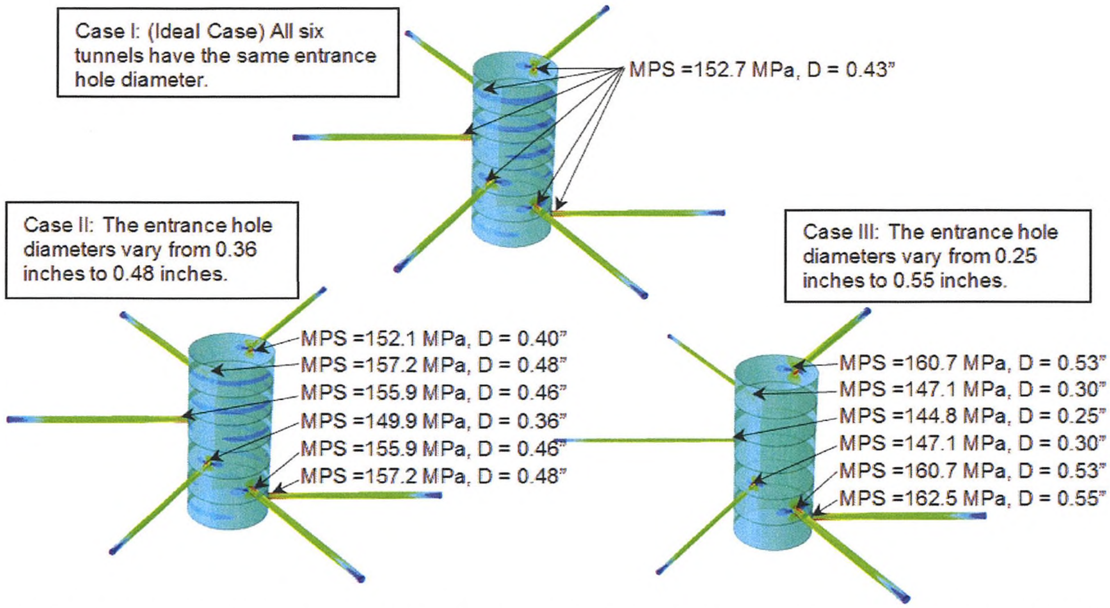

Fig. 5—Contour plots of the local maximum principal stress (MPS) on the surfaces of the perforation tunnel and the wellbore. The local maximum principal stress (MPS) is always on the surface of the perforation tunnel near the entrance, so the entrance-hole diameter greatly contributes to fracture initiation.

To derive a fracture initiation criterion, we will consider the following hydraulic fracturing process. As the fluid is injecting into the well, a very high pressure will build up on the casing surface and the perforation tunnel surface, resulting in locally elevated stresses in the reservoir rock near the perforation tunnel. In general, the fracture will initiate when the maximum principal stress, σ_1 of the rock reaches the tensile failure strength of the rock, T_{fail} which can be written as:

$$\sigma_1 = T_{fail}. \qquad (1)$$

Furthermore, based on the present finite element analysis, the hydraulic pressure generated by the injection fluid is linearly proportional to the calculated local max principal stress, such that

$$\sigma_1 = Kp \qquad (2)$$

Where K is the coefficient, which is a function of reservoir rock properties, as well as the geometry of the perforation tunnel. Substituting (1) into (2), we obtain the relation between the breakdown pressure, p_{bd} and the tensile failure strength of the rock, T_{fail} as

$$p_{bd} = T_{fail}/K \qquad (3)$$

Eq. 3 indicates that for a given reservoir rock (i.e., T_{fail} is a constant), the breakdown pressure is proportional to the inverse of the coefficient K. A larger value of K leads to a reduced breakdown pressure. Furthermore, according to the numerical results in Fig. 3, for a given pressure, the local maximum principal stress (MPS) increases as the hole diameter decreases. For example (i.e., in Case 3), for the smallest entrance-hole diameter ($D = 0.25$ *in.)*, the MPS equals 144.8MPa, whereas for the largest entrance-hole diameter ($D = 0.55$ *in.*), the MPS is 162.5MPa. Consequently, the larger the entrance-hole diameter, the larger the value of the coefficient K. Finally, we can conclude that for a given reservoir rock, the breakdown pressure will be reduced as the perforation tunnel diameter increases. This conclusion agrees with previous work that documents the importance of casing hole size over penetration (Behrman and Nolte 1998).

Although breakdown pressure can be reduced locally by a larger entrance-hole diameter, the consistency of all hole diameters is also critical for a successful breakdown and stimulation. An important factor affecting the efficiency of hydraulic stimulation process is the ability to pass fluid through all perforations, specifically those aligned with the preferred fracture plane, which enables each hole to contribute to a successful breakdown and stimulation. If the variation of the entrance-hole diameter of the neighboring perforation tunnels is too large, then the fracture will initiate at the entrance of the larger hole, leaving the smaller holes less effective and possibly creating a tortuous path as the fracture grows and aligns itself with the preferred fracture plane. This is because after the fracture occurs at a single perforation hole, the diameter of the damaged

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