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ENHANCEMENT OF THE COMPLETION EFFICIENCY OF PERFORATION TUNNELS IN PETROLEUM WELLS

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ABSTRACT

The objective of perforating is to maximize well productivity by establishing good connectivity between the wellbore and formation. The conventional method of perforation – perforation by shooting (PS) cannot achieve expected wellbore productivity due to a region of reduced permeability around the perforation tunnel. In this study, it has been established that permeability is decreased in the range of 30%-75% due to the implementation of the PS technique compared to the openhole completion. As a result, a new perforation technique – perforation by drilling (PD) has been proposed in this paper. To simulate a perforated completion, cylindrical sand samples (0.0572 m OD) consolidated with cement with varying porosity were prepared. These samples were perforated (0.0136 m ID) by the PS, PD and Casting techniques. Perforations created by the Casting techniques are considered the ideal, openhole perforation tunnel. Fluid flow rates and differential pressure across the perforated samples were measured for three different types of samples using "Geotechnical Digital System" triaxial testing set-up. Fluid flow rates with changing differential pressure and finally pressure build-up data with time indicates the PD technique can achieve better wellbore productivity compared to the PS technique. Results indicate that at 100 kPa differential pressure the PS, PD and Casting techniques can achieve 0.20 mL/s, 0.65 mL/s and 1.00 mL/s fluid flow rates respectively across a sample.

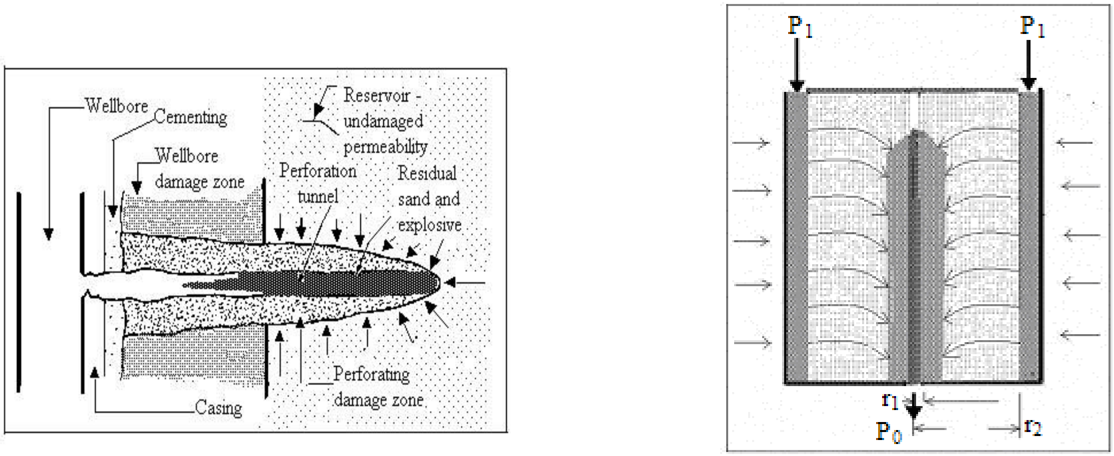
Keywords: Formation damage, perforations, productivity index, skin factor.

INTRODUCTION

The process of perforation in petroleum wells is vital in many oil production operations. To achieve effective fluid flow communication between a cased wellbore and a producing reservoir, a gun perforator punches a geometrical pattern of perforations through the casing, cement sheath and the producing formation. This paper demonstrates the extent of the perforation damage created by the conventional perforation by shooting (PS) technique and proposes a new alternative perforation technique - perforation by drilling (PD). Inadequate flow efficiency of the PS completions has been a major problem since the first use of the PS technique in the 1930s [1]. The problem was initially attributed to restricted perforation area through the casing compared to the larger surface area of an openhole completion of the same length. However, as early as 1950, experimental studies [2] indicated that, with proper penetration and shot density, the flow efficiency of a perforated system should be higher than that of a comparable - length openhole completion. Unfortunately, even with proper geometry, experimental and field performance fell short of predicted results [3-5]. Investigations conducted in this study indicate that the PS technique reduces permeability around the perforation tunnel in the range of 31-73 percent compared to the undamaged formation.

EXPERIMENTAL SET-UP AND PROCEDURE

The simulation of in-situ conditions in a laboratory model is delicate. Most of the perforation experiments conducted so far are based on some simplified assumptions.



(a) Actual perforation tunnel in reservoir wells.

(b) Simulated perforation tunnel.

Fig. 1. Simulation of the actual reservoir (a) in the laboratory (b).

In most of the cases, a number of reservoir parameters are neglected due to the difficulty to implement them in a laboratory experiment. In this study, a limited confining pressure, axial load and drawdown pressure were maintained to simulate the "in-situ" conditions. The methodology of the entire experimental program was as follows:

1. Simulation of the actual field reservoir with cylindrical sand samples. Figure 1 shows the simulated perforation tunnel, which resembles an actual perforation tunnel in the wellbore. In the actual set-up of the experiment in the lab the sand samples were positioned vertically. The samples were vertical to obtain the radial flow characteristics from the radial flow model equation.
2. Preparing sand samples perforated by the PS, PD and Casting techniques. In the Casting technique it was possible to obtain a desired geometry of the perforation tunnel. In the PD technique it was also possible to obtain a desired geometry of the perforation tunnel, but around the circumference of the tunnel a minute amount of damage possibly was produced due to the drilling operation itself. In the PS technique it was never possible to achieve such geometry. Rather, the solid sand samples were always shattered. As a result, the damage zone around the tunnel was created by inserting the shattered sand particle, which was obtained during the hooting operation in the lab. Similar to the actual shooting perforation tunnel in reservoirs, in the lab this debris introduced the damage zone, which simulated the PS technique.
3. Measuring fluid flow rate and differential pressure across the perforated samples, using geotechnical triaxial testing set-up.

Geotechnical Triaxial Testing (GTT) Set-up

Figure 2 shows the schematic diagram of the GTT set-up (by GDS Inc.) loaded with a cylindrical sand sample (Item 1 in Figure 2). The hydraulic cell of the triaxial testing set-up is coupled with three different pressure/volume controllers. (Item 2, 3 and 4 in Figure 2).The set-up can generate upto10 kN of axial load (Item 8 in Figure 2). The axial load is required to prevent any leakage across the two flat faces (Items 10 and 11 in Figure 2) of the cylindrical samples. A load cell (Item 9 in Figure 2) senses the amount of applied axial load. The set-up is also connected to a water reservoir (Item 6 in Figure 2) to supply sufficient fluid (water) and a computerized data acquisition system (Item 12 in Figure 2) to monitor, acquire, process and store data. Two different types of experiments were conducted with GTT set-up. Flow rate was measured across the perforated cylindrical samples at a desired differential pressure and differential pressure was measured across the perforated samples with changing time until a specific flow rate was achieved.

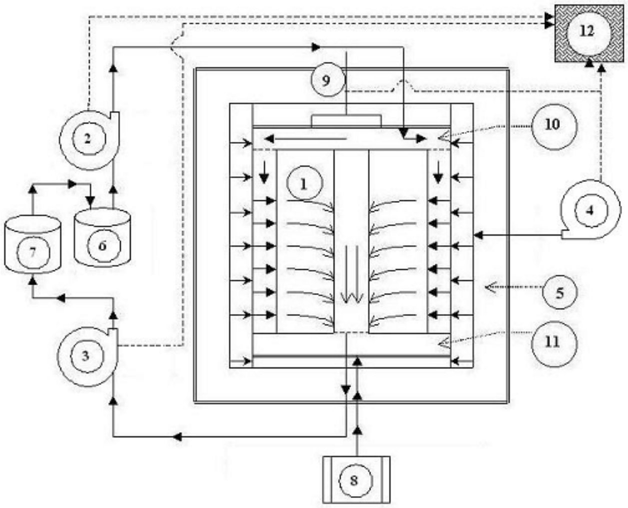


Fig. 2. Schematic of the experimental set-up.

Core Samples Preparation

Three different samples were prepared by varying the amount of sand, cement and water properties. The composition of samples is shown in Table 1. Subsequent permeability and porosity date are given in Table 2. The core samples were perforated by three different methods; PS, PD, and Casting.

Table 1. Ingredients of the samples used in the experiments

Type	Ingredients		
	Sand (g)	Cement (g)	Water (ml)
Sample A	500	200	130
Sample B	600	150	130
Sample C	650	100	130

Table 2. Permeability and porosity values used for mathematical modeling

	Permeability, m^2 (10^{12})			Porosity (%)
	PS	PD	Casting	
Sample A	5	7	11	0.15
Sample B	11	16	20	0.24
Sample C	9	20	34	0.28

NUMERICAL STUDY

In this study an axially symmetric radial 1-D time dependent porous media flow model was introduced to describe the fluid flow behavior and assess the pressure build-up across the perforated samples. After combining the continuity equation, momentum equation (Darcy's law) and compressibility equations, the final form of the equation can be written as:

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} + c\left(\frac{\partial p}{\partial r}\right)^2 = \frac{\phi c_t \mu}{k}\frac{\partial p}{\partial t} \qquad [1]$$

The radial diffusivity equation is a nonlinear partial differential equation, which describes the pressure at any radius, r, at any time, t, across a perforated system. Because of its nonlinearity, this equation is difficult to solve using analytical techniques. Equation [1] has been solved by two different methods: (1) Exponential Integral (EI) method [6] (2) Adomian Decomposition (AD) method [7].

RESULTS AND DISCUSSIONS

Productivity Index

One of the powerful tools to measure the perforation efficiency is the "productivity index". To elucidate the "productivity index", flow rates for a series of changing differential pressure were measured in the experiment. Flow rates through the perforated samples with changing differential pressure are presented in Figure 3. In Figure 3, it is observed that perforated samples created by casting technique results in the higher flow rates compared to the PD and PS techniques. This is due to the fact that casting does not induce any damage around the perforation tunnel.

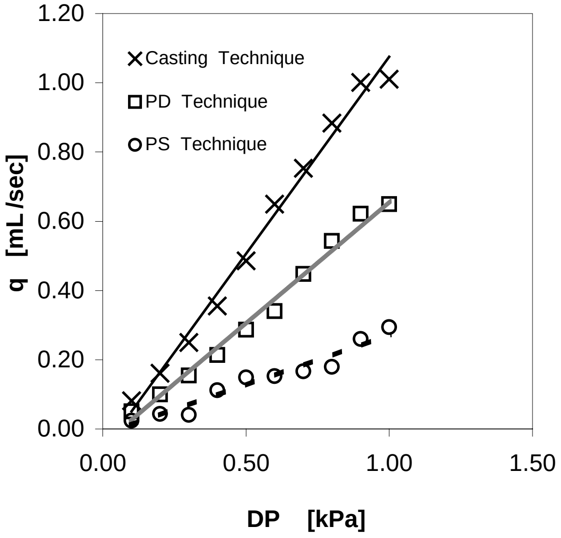


Fig. 3. Flow rate among the PS, PD and Casting techniques with changing differential pressure.

In the PD technique the drilling process does not generate any transient shock wave around the perforation tunnel. As a result, less fine particles are produced. Consequently, few fine particles are redistributed. However, due to the nature of the drilling process a small amount of damage is likely to take place around the perforation tunnel. Due to this amount of damage, insignificant flow restriction may also occur in the PD technique.

In the PS technique, once fluid starts to flow, fine particles are redistributed around the perforation tunnel. This redistribution likely reduces the pore throat size in the porous medium. This reduction in pore throat size has profound effect on permeability. As a result, significant permeability reduction occurs leading to lower flow rates at the same differential pressure.

Pressure Buildup Test

The experimental and theoretical (EI method) data is presented in Figure 4. From this figure it is observed that differential pressure across the perforated cylindrical samples (PD, PS and Casting) increases if a particular volume of fluid is injected through the samples. From the same figure it is also evident that the PS technique experiences a greater pressure differential followed by the PD and PS techniques at the same volume of injected fluid. This is due to the redistribution of the particles around the "crushed zone" of the perforation tunnel once fluid starts to flow. As mentioned earlier, it is also believed that the minute amount of crushed zone is formed in the PD technique due to the drilling process itself. The formation damage is less than that of the PS technique. The Casting method was taken as an ideal open-hole perforation tunnel. It is believed that no crushed zone was formed around the perforation tunnel. As a result, the differential pressure in the Casting method is the lowest compared to the PS and PD techniques.

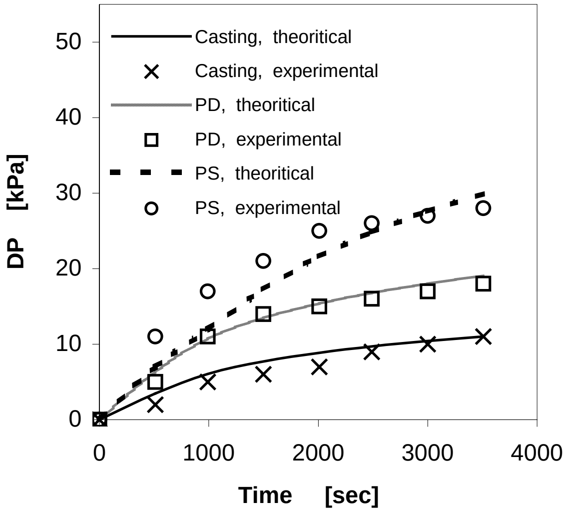


Fig. 4. Comparison of experimental and theoretical (EI) observations of differential pressure.

The experimental and theoretical data obtained by the AD method is presented in Figure 5. In Figure 5 the same trend is observed as observed in Figure 4. Same conclusions can be reached from this figure as the previous figure.

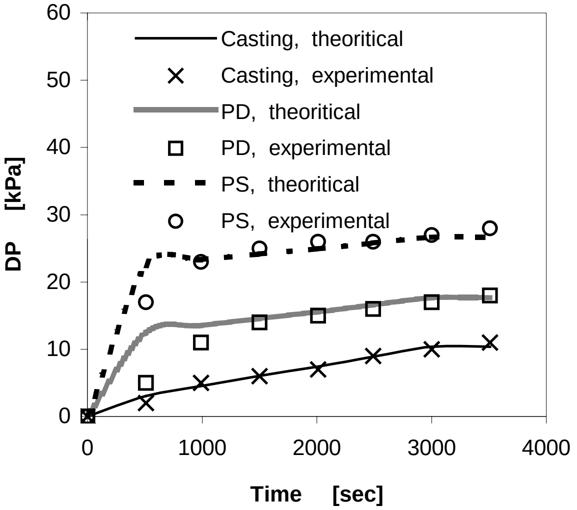


Fig. 5. Comparison of experimental and theoretical (AD) observations of differential pressure.

From Figure 4 and 5 it is evident that both the EI and AD methods can accurately predicts the flow field in the sand samples. Since in the EI method the second order non-linear term is neglected it would be more appropriate to use the AD methods in higher-pressure condition.

Deterioration of Permeability

Permeability for each solid sample was calculated for a particular flow rate obtained for a given differential pressure. From Figure 6, it is observed that decrease in permeability in samples C, B and A is 73.30%, 45.50% and 31.63% respectively due damage by the PS technique and 40.30%, 20.26% and 10.71% respectively due to damage caused by the PD technique. In both cases, the Casting technique was taken as the ideal one.

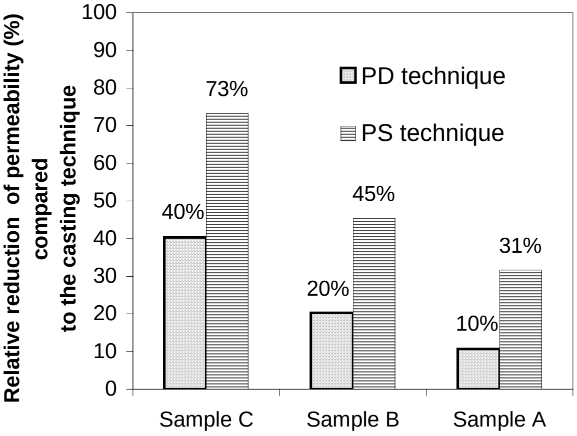


Fig. 6. Percentage decrease in permeability in the PS and PD technique compared to the Casting technique.

CONCLUSIONS

The following conclusions can be reached from the investigations conducted in the study:

1. A uniform round perforation tunnel was not achieved in the perforation process conducted by the PS technique.

2. Due to a mainly high amount of fine particles generation (before fluid starts to flow) and redistribution/migration (after fluid starts to flow), higher formation damage is projected in the PS technique. On the other hand, due to less fine particle generation, less formation damage is resulted in the PD technique.

3. Experimental results reveal that higher fluid flow rate and less pressure drop is possible in the PD technique compared to the PS technique. This behavior is favorable for the increased hydrocarbon production in the reservoir well.

4. A comprehensive model to address fluid flow behavior in the perforation tunnels created by the PS and PD techniques has been introduced in this study. Partial differential radial diffusivity equation for single-phase radial flow has been used as the core governing equation for the type of flow believed to take place in such circumstances.

5. The experimental results obtained in the PD technique will have to be scaled-up, so that it can be implemented in field operation.

6. Several runs have to be conducted in downhole condition so that the superiority of the PD technique compared to the PS technique can be established from experimental, numerical and field data.

NOMENCLATURE

Abbreviations

AD	Adomian Decomposition
EI	Exponential Integral

Symbols

b	formation volume factor
c_t	total isothermal compressibility factor (Pa^{-1})
h	height of the sample (m)
k	permeability (m^2)
P	pressure (Pa)
DP	differential pressure (kPa)
q	fluid flow rate (mL/sec)
Q	fluid flow rate (mL/sec)
r	space coordinate in flow direction (m)
t	time (sec)

Greek Letters

μ	viscosity of fluid (mPa.s)
ϕ	porosity of the porous medium(%)

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