Optimization of Perforation Tunnels Productivity in Reservoirs Diminishing the Formation Damage

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Abstract

The objective of perforating is to maximize well productivity by establishing good connectivity between the wellbore and formation. 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 implement 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) with varying strength and 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 rate with changing differential pressure and finally pressure build-up data with time profile indicates the PD technique can achieve maximum 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. An important measure of flow efficiency or productivity of perforation completions can be referred to as skin factor (s) and productivity index (PI). In this paper, the performance of the PS, PD and Casting technique was measured in terms of skin factor. Fluid flow rate and differential pressure across the perforated samples were measured for three different types of samples using "Geotechnical Digital System" triaxial testing set-up.

Keywords: Formation damage; Perforations; Productivity index; Skin factor

Introduction

The process of perforation in petroleum wells is vital in oil production operation. 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 (Bell et al., 1995). 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 in 1950, experimental studies (Howard et al., 1950; McDowell et al., 1950) 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 (Arora et al., 2000; Kaiser et al., 2002; Underdown et al., 2003). Investigation conducted in this study indicates that the PS technique reduces permeability around the perforation tunnel by approximately in the range of 31-73 percent compared to the undamaged formation.

Experimental Set-up and Procedure

Rationale

The simulation of in-situ conditions in a laboratory model is delicate. Most of the perforation experiments conducted so far is based on some simplified assumptions. 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" The methodology of the entire experimental program was as follows:

1. Simulation of the actual field reservoir with cylindrical sand samples. Fig. 1 shows the simulated perforation tunnel, which resembles actual perforation tunnel in the wellbore.
2. Preparing sand samples perforated by the PS, PD and Casting techniques.
3. Measuring fluid flow rate and differential pressure across the perforated samples, using geotechnical triaxial testing set-up.

Geotechnical Triaxial Testing (GTT) Set-up

Fig. 2 shows the schematic diagram of the GTT set-up (by GDS Ins. 2003) loaded with a cylindrical sand sample (Item 1 in Fig. 2). The hydraulic cell of the triaxial testing set-up is coupled with three different pressure/volume controllers. (Item 2, 3 and 4 in Fig. 2 The set-up can generate upto 10 kN of axial load (Item 8 in Fig. 2). The axial load is required to prevent any leakage across the two flat faces (Items 10 and 11 in Fig. 4) of the cylindrical samples. A load cell (Item 9 in Fig. 2) senses the amount of applied axial load. The set-up is also connected to a water reservoir (Item 6 in Fig. 2) to supply sufficient fluid (water) and a computerized data acquisition system (Item 12 in Fig. 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.

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. The core samples were perforated by three different methods; PS, PD, and Casting.

Received 31 August 2005, Accepted 15 May 2006

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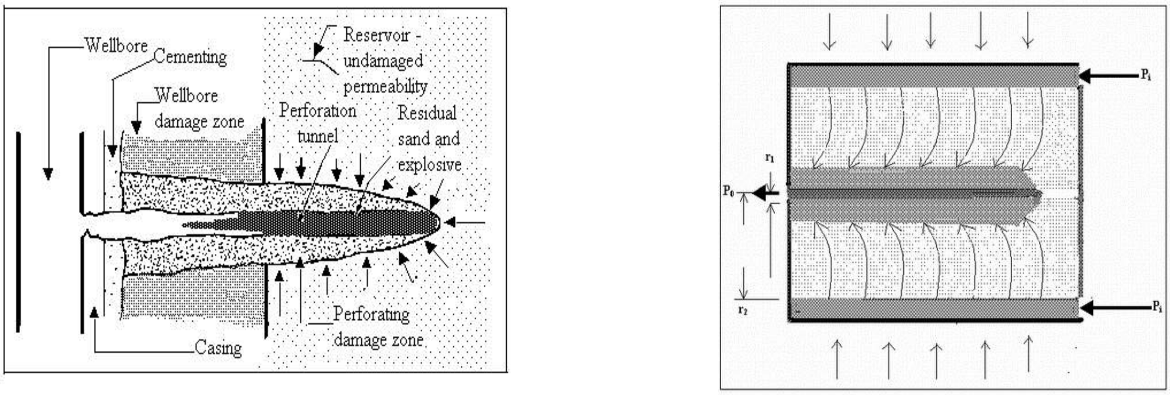
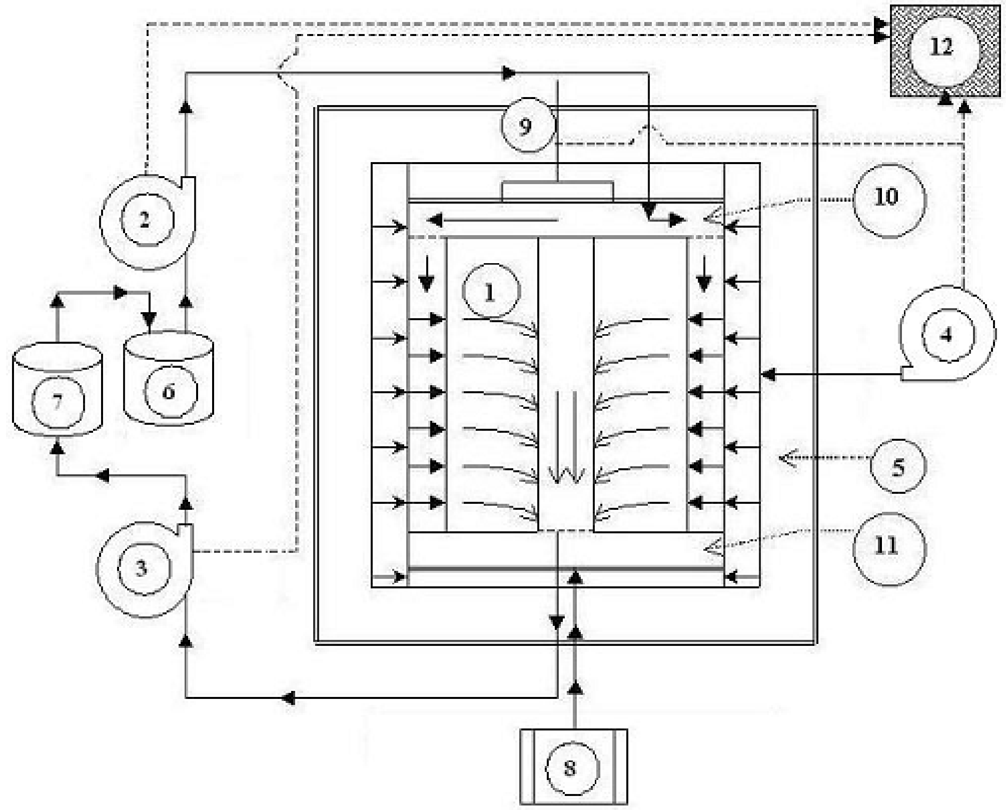


(a) Actual perforation tunnel (sand sample)

(b) Simulated perforation tunnel

Fig. 1 Simulation of the actual reservoir in the laboratory



1. Perforated cylindrical sample, 2. Fluid injection pressure/volume controller, 3. Fluid receiving pressure/volume controller 4. Confining pressure/volume controller, 5. Hydraulic Triaxial cell, 6. Water reservoir, 7. Deaeration chamber, 8. Axial Loading system, 9. Load Cell, 10. Upper faceplate, 11. Lower faceplate, 12. Computerized data acquisition system.

Fig. 2 Schematic of the experimental set-up

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

Numerical Study

In this study 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:

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

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.

Eq. (1) has been solved by two different methods; i.e., Exponential Integral (EI) method (Mian 1992) and Adomian Decomposition (AD) method (Biazar et al. 2002). If it is assumed that the pressure gradient across the perforated sample is small, the second order term in Eq. (1) can be neglected as it confers very small value compared to other terms in the equation. In this condition, Eq. (1) reduces to a linear equation, which can be solved simply by EI method. After considering the above assumption, Eq. (1) simplifies to

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} = \frac{\phi c_t \mu}{k}\frac{\partial p}{\partial t} \tag{2}$$

Eq. (2) can be solved using EI method as shown in Mian (1992). Eq. (1) has been solved using the AD method, taking into consideration the nonlinear term. Methodology to solve Eq. (1) by the AD method can be found in Biazar et. al. (2002).

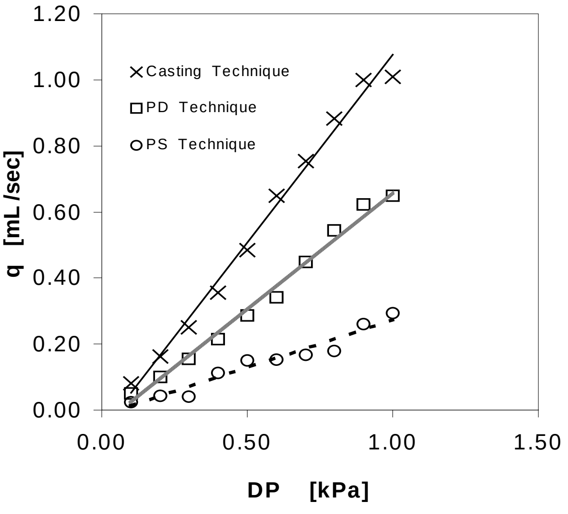


Fig. 3 Flow rate among the PS, PD and Casting techniques with changing differential pressure

Results and Discussion

Productivity Index

One of the powerful tools to measure the perforation efficiency is the "productivity index. To envisage an idea about 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 Fig. 3. In Fig. 3, it is observed that perforated samples created by casting technique results in the maximum flow rate compared to the PD and PS techniques. This is due to the fact that casting does not induce any damage around the perforation tunnel.

On the other hand, 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 small amount of damage is likely to take place around the perforation tunnel. Due to this minute 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.

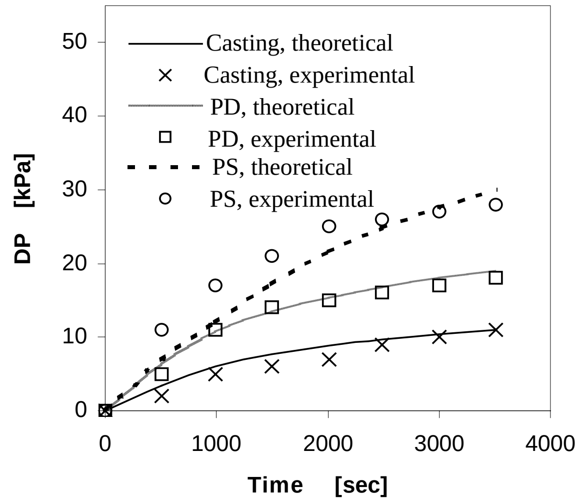


Fig. 4 Comparison of experimental and theoretical (EI method) observations of differential pressure

Pressure Buildup Test

The experimental and theoretical (EI method) data is presented in Fig. 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 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. This 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.

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

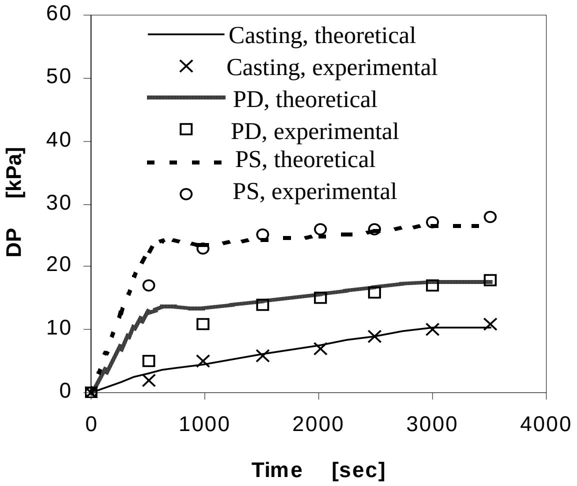


Fig. 5 Comparison of experimental and theoretical (AD method) observations of differential pressure

Comparison between the EI and AD Methods

Comparison between the EI and AD methods is shown in Fig. 6. Although Fig. 4 and Fig. 5 show that both the EI and AD methods can accurately predict the flow field in the sand samples, it would be more appropriate to use the AD method in higher-pressure condition as the second order nonlinear term is neglected in the EI method.

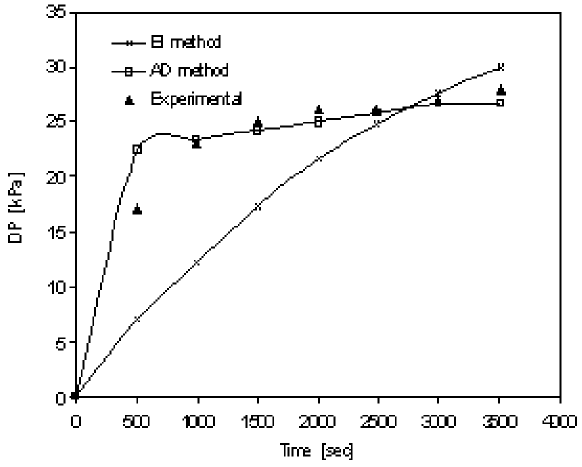


Fig. 6 Comparison between the EI and the AD methods for a constant fluid injection pressure

Deterioration of Permeability

Permeability for each sample was calculated for a particular flow rate obtained for a given differential pressure. From Fig. 7, 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.

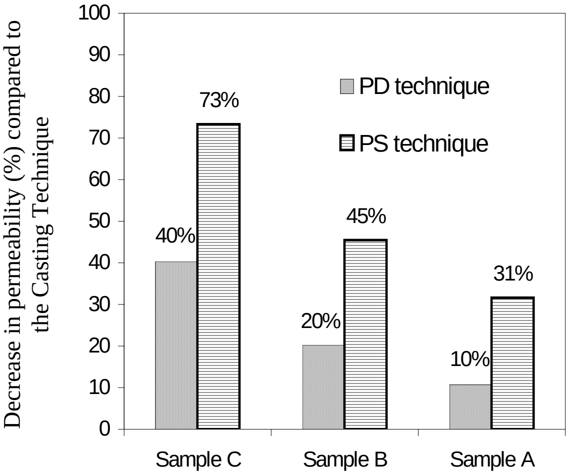


Fig. 7 Percentage decrease in permeability in the PS and PD technique compared to the Casting technique

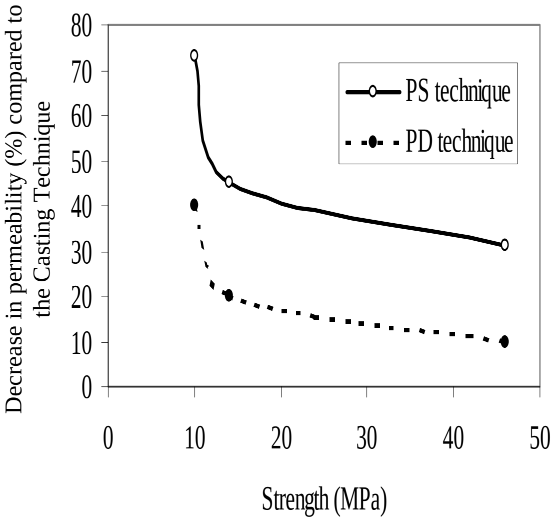


Fig. 8 Percentage decrease in permeability compared to the Casting technique with compressive strength of the samples

Decrease in permeability due to the use of the PS technique compared to the PD technique can be related to the strength of the sandstone sample. Experimentally it was observed that damage caused by the PS technique is higher in the low strength sample as shown in Fig. 8. The decrease in permeability is less significant in the high strength material. Reservoir mechanical strength varies from formation to formation. Thus, it can be concluded that in a weak, unconsolidated formation, the PS technique incurs more damage compared to a strong, fully consolidated formation. In weak sandstone, frail bond exists among the grains of the reservoir rock. These loosely packed sand grains are susceptible to the trapping fine particles easily. In addition, sudden shock waves due to perforating using the PS technique shatter the rock grain more easily than hard sandstone and eventually more fine particles are produced. These fine particles plug the pore throats reducing permeability. Thus in Table 2 it is evident that in case of the PS method the permeability of ‘Sample C’ becomes lower than ‘Sample B’, whose porosity is lower.

Table 2 Permeability and porosity 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

Conclusions

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

1. Uniform round perforation tunnel was not achieved in the perforation process conducted by the PS technique.
2. Due to 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.

Acknowledgments

The authors wish to acknowledge the financial support used to carry out this study provided by various Canadian governmental and industrial organizations.

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)
μ	Viscosity of fluid (mPa.s)
ϕ	Porosity of the porous medium(%)

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