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3.1

Upstream technologies. Novel well and production architecture

3.1.1 Introduction

For over a century, the centrepiece of production architecture and associated technologies of the oil and gas industry has been a vertical well. The production philosophy has been quite simple: based on the best available geological and geophysical data, locate the most likely underground spots for the accumulation of oil and gas, drill a vertical hole, case and cement it to give it long life and to prevent migration of reservoir fluid into adjacent zones. The majority of the initial wells were completed openhole along the producing zone to facilitate the unimpeded flow of oil. But this model soon proved to cause later production problems: excessive and uncontrolled water and gas flow accompanied by rapid drop in reservoir pressure and well productivity, lack of access to the zone in poorly consolidated formations, and very limited remedial services and treatments to address flow problems. As new technologies were developed by the oil and gas and other industries, the production schemes changed to take advantage of the new developments. Among the borrowed technologies are reservoir engineering theories from hydrology, the use of shaped charges for perforation based on military technology, cementing materials from construction industries, computer modelling and simulation from civil and aeronautical engineering, and many more. New technologies developed by the industry itself have also proved tremendously valuable in all phases of operations. Notable among these are electrical logging, hydraulic fracturing, Logging While Drilling (LWD), 3D seismic, new drill bits, and computerized on-site data acquisition systems. Application of these technologies required the development of new tools and equipment, materials, and the engineering know-how to perform computations necessary for their effective day-to-day use. All of the tremendous developments in all aspects of many different operations were focused on the same basic production scheme: developing, completing, and producing from a vertical well. Today, the art, science, and technology of drilling and completing a vertical well have reached a very high level of maturity.

In spite of all efforts, however, production from some reservoirs proved highly challenging and beyond the existing capabilities of the industry. Even though large amounts of oil and gas were known to exist underground, the available techniques and production architectures were not sufficient to allow their economical exploitation. For example, the Austin Chalk formation in Central Texas was known to contain large volumes of hydrocarbon, but the productivity of wells drilled into it was random and unpredictable. For years operators grappled with trying to find a consistent suitable production scheme, but with very limited success. A similar situation existed in the Rospo Mare reservoir, offshore Italy in the Adriatic Sea, operated by Elf with Agip as a main partner. After a great deal of work, the collaborative efforts of Elf, Agip and Institut Français du Pétrole led to the conclusion that production of this field required different production architecture. They finally decided that the best way to produce from the fractured carbonate reservoir was by drilling a horizontal hole and intersecting the existing natural fractures in the formation.

Even though horizontal drilling had been attempted in the 1940s, it had been completely abandoned as too cumbersome and inefficient. The general belief among experts was that many of the beneficial results of a horizontal hole could also be achieved by hydraulically fracturing a vertical well. In fact, theoretical developments had shown a direct correspondence between the two production methods. While horizontal drilling was an unknown territory with a very small basis of technical and operational support, hydraulic fracturing was a well-established and common practice in the industry, with all the required tools, equipment, materials and technologies in place. Lack of technical and operational support base for horizontal wells also meant scarcity of know-how, higher risk, and greater cost. In spite of these obstacles, it was decided to undertake the project, and thus began the next generation of production architecture, which is shaping the industry at the present time. The success of this pioneering effort has led to the development of an entirely new production architecture that is based on a horizontal well as its centrepiece. From the main bore multiple lateral branches are extended into the same or other reservoirs, thus substantially increasing contact with the hydrocarbon-bearing formation. Evolution of this system led to recognition that effective production management based on this complex scheme requires the ability to control and regulate flow from or into different branches, and thus recognition of the need for downhole flow regulators and intelligent wells. Since success of horizontal holes depends on much more accurate placement in the reservoir, new and advanced drilling and navigation systems had to be developed to augment the existing technology. Tools and techniques of reservoir description also had to undergo major changes to allow better definition of the distribution and flow of oil and gas, which led to downhole sensor technology development. To take full advantage of the above developments, one also needs hybrid simulators and decision-making processes to economically optimize fluid flow into or out of the reservoir. All of these procedures have led to the formation of a new frontier in oil and gas production, one that is likely to shape the future of oil and production.

Below we review historical, technical and operational aspects of each of these technologies. In particular, the discussion covers horizontal holes, multilaterals, intelligent downhole flow regulators, and the technologies that enable their effective utilization. These enabling technologies include geosteering, permanent downhole measurement devices, and novel completion techniques, among others.

3.1.2 Horizontal drilling

History of horizontal drilling

The first modern horizontal holes were drilled in France: two in Lacq and one in Castéra-Lou (Giger *et al.*, 1984). All of these were land wells. The main objective of the first two wells was to understand and develop the technology that was required for effective production of Rospo Mare reservoir, offshore Italy in the Adriatic Sea. The first two of these were drilled in Lacq Supérieur at the relatively shallow depth of around 2,000 ft (600 m). The first well, Lacq 90, was drilled in 1979, and its horizontal section was 360 ft (108 m) long, completed with an un-cemented slotted liner. The next well, Lacq 91, had a horizontal section 1,120 ft (336 m) long. Various completion techniques were tried in this well to isolate part of the well and to reduce flow of water. The third well, Castéra-Lou 110, was used to demonstrate the feasibility of drilling at a depth of 9,000 ft (2,700 m) and to experiment with various completion techniques. This well penetrated 1,000 ft of reservoir (300 m), with a 490 ft (147 m) horizontal section, and produced at a rate of 440 bbl/d (barrels of oil per day) or 70 m^3/d. Its production was more than eight times higher than the neighbouring vertical wells, thus proving the viability of the concept.

Rospo Mare, the next horizontal well, was drilled in the main target of the research. The formation is a carbonate with very low porosity where much of the oil is contained in natural fractures and vugs. The reservoir fluid is heavy oil, with API gravity of 11° and viscosity of 300 cP. The vertical pilot hole was 9 5/8″ (about 24.4 cm) and the horizontal open hole was 8 1/2″ (about 21.6 cm) in diameter. The vertical location of the horizontal section was 230 ft (70 m) above the oil/water contact. The horizontal section penetrated 2,000 ft (600 m) of the reservoir. This well produced 3,600 bbl/d (570 m^3/d), more than twenty times that of the other wells in the same field.

The next major development in horizontal drilling was led by Maersk Oil & Gas in Dan field. Their main intent was also to improve productivity of the low permeability chalk. However, accomplishment of their production objectives required the creation of multiple fractures in the horizontal hole. To do this, they needed to successfully install and cement a liner in the horizontal section in order to isolate the well for multiple fracture treatments. Furthermore, creation of multiple fractures required new cementing techniques and materials for horizontal wells, highly specialized downhole tools, multiple trips, and several milling and cleaning operations, as well as specialized fracturing materials and techniques. All these issues were addressed and resolved through collaborative efforts between Maersk, Halliburton and Baker Oil Tools (Brannin *et al.*, 1990; Damgaard *et al*., 1992; Owens *et al*., 1992). The result was a successful completion of long cased and cemented horizontal holes with multiple fractures and substantially higher productions.

In spite of this spectacular success, the growth of horizontal hole technology was relatively slow. It took more than a decade and many successes and failures before the industry developed the required equipment, techniques, technologies and comfort-level to consider horizontal drilling as a viable option for field development.

Productivity of horizontal wells

Several different equations have been developed for computation of the productivity of horizontal wells. Because of the complexity of the problem, most of these are approximations of the analytic solutions; however, they are accurate for engineering computations.

Babu and Odeh's solution (1989) considers the pseudo-steady state flow. Assuming the reservoir geometry defined in **Fig. 1**, and that there is no formation damage, their solution for the flow rate q is given by:

$$q=\frac{7.08\cdot10^{-3}\,b\sqrt{k_x k_z}(\bar{p}_R-p_{wf})}{B\mu\left(\ln\frac{A^{1/2}}{r_w}+\ln C_H-0.75+s_R\right)}$$

and the productivity index, J, is given by:

$$J=\frac{7.08\cdot10^{-3}\,b\sqrt{k_x k_z}}{B\mu\left(\ln\frac{C_H A^{1/2}}{r_w}-0.75+s_R\right)}$$

where q is the flow rate, stb/d (stock tank barrel/d); A is the drainage area of the horizontal well, ft^2; B is the formation fluid volume factor, rb/stb (reservoir barrel/stock tank barrel); μ is the oil viscosity, cP; b is the drainage distance of horizontal hole in y direction, ft; C_H is the geometric factor; k_x and k_z are the permeability in directions x and z, in mD (where x, y, and z are coordinates of a point in the reservoir); $\bar{p}_R$ is the average reservoir pressure in drainage volume, psi; p_{wf} is the average flowing bottomhole pressure, psi; r_w is the wellbore radius, ft; s_R is the skin resulting from partial penetration.

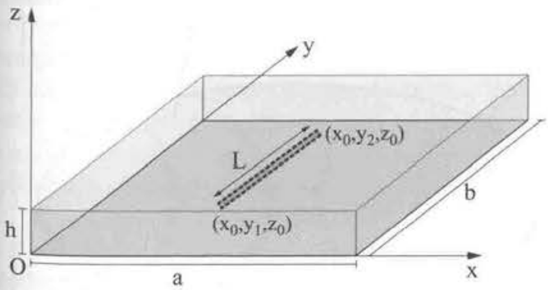

Fig. 1. Horizontal hole layout in the reservoir.

The approximate expression for C_H is:

$$\ln C_H=6.28\frac{a}{h}\sqrt{\frac{k_z}{k_x}}\left[\frac{1}{3}-\frac{x_0}{a}+\left(\frac{x_0}{a}\right)^2\right]-$$
$$-\ln\left(\sin\frac{180°z_0}{h}\right)-0.5\ln\left(\frac{a}{h}\sqrt{\frac{k_z}{k_x}}\right)-1.088$$

where a is the drainage distance of horizontal hole in x direction, ft; h is the drainage distance of horizontal hole in z direction, ft; x_0 is the x coordinate of centre of well; z_0 is the z coordinate of centre of well.

Denoting by L the length of horizontal hole, if $L=b$ (fully penetrating well), then $s_R=0$. If $L<b$, then the partial penetration skin, s_R, is given for two special cases.

In the first case:

$$\frac{a}{\sqrt{k_x}}\geqslant\frac{0.75b}{\sqrt{k_y}}\geqslant\frac{0.75h}{\sqrt{k_z}}$$

where k_y is the permeability in direction y, then:

$$s_R=P_{xyz}+P_{xy}$$

$$P_{xyz}=\left(\frac{b}{L}-1\right)$$
$$\left[\ln\frac{h}{r_w}+0.25\ln\frac{k_x}{k_z}-\ln\left(\sin\frac{180°z}{h}\right)-1.84\right]$$

$$P_{xy}=\frac{2b^2}{Lh}\sqrt{\frac{k_z}{k_y}}\left\{F\left(\frac{L}{2b}\right)+\right.$$
$$\left.+0.5\left[F\left(\frac{4y_{mid}+L}{2b}\right)-F\left(\frac{4y_{mid}-L}{2b}\right)\right]\right\}$$

where F denotes a function.

Pressure computations are made at mid-point along the well length, $y_{mid}=(y_1+y_2)/2$. The values of $F(L/2b)$, $F[(4y_{mid}+L)/2b]$ and $F[(4y_{mid}-L)/2b]$ in the above equations are computed by replacing y with the appropriate arguments in:

$$F(y)=-(y)[0.145+\ln y-0.137\,y^2]$$
$$y=\frac{L}{2b}\quad\text{or}\quad y=\frac{4y_{mid}\pm L}{2b}\leqslant$$

$$F(y)=(2-y)[0.145+\ln(2-y)-0.137\,(2-y)]$$
$$y=\frac{4y_{mid}\pm L}{2b}\geqslant$$

In the second case:

$$\frac{b}{\sqrt{k_y}}<\frac{1.33a}{\sqrt{k_x}}>\frac{h}{\sqrt{k_z}}$$

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