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Application of Horizontal Waterflooding to Improve Oil Recovery from Old Oil Fields

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Abstract

This paper discusses the results of the application of horizontal waterflooding technology to improve the recovery of oil from older fields. A multi-disciplinary approach combining geological interpretations, rock mechanics evaluations, reservoir simulation studies, and drilling technologies was employed. A range of reservoir conditions in which the technology is viable is discussed and the results of the field tests are presented.

The major focus has been on the shallow sandstone reservoirs in northeast Oklahoma and southeast Kansas. It has been demonstrated that additional oil can be recovered in several different reservoir environments in these older fields, by utilizing a combination of horizontal and vertical wells. Two previous SPE papers described the results of a Department of Energy (DOE) supported horizontal waterflooding pilot located in the Wolco Field, Osage County, Oklahoma.

The technology has continued to evolve over time. The key to assessing the potential for a horizontal well application is a thorough understanding of the reservoir description, including the oil saturation, depositional environment, reservoir pressure, permeability, and an evaluation of any prior production and/or injection. Other parameters include the length, spacing, positioning and orientation of the injectors and horizontal producers in the target zone. Use of rotary-steerable drilling equipment has made it possible to drill underbalanced, short-radius horizontal laterals at a low cost. Special procedures have been adopted to permit the transport of openhole logging equipment through the short-radius curve to the end of the lateral, providing a good description of reservoir properties and detecting the presence and orientation of natural fractures.

Results from several successful horizontal well projects are discussed. These include (1) two horizontal waterfloods in shallow Bartlesville sandstone reservoirs, (2) recovery from a rim of moderately heavy oil underlain by water, and (3) an application of horizontal waterflooding in a moderately heavy oil reservoir.

Introduction

The major objectives of this paper are to discuss the industry trends in the application of horizontal wells in flooding operations and to describe the specific experiences of Grand Directions, LLC (Grand), a division of Grand Resources, Inc. Grand has been developing and applying horizontal well technology during the past four years, with a focus on the Pennsylvanian sands in the mid-continent area. Significant advancements have been made in a variety of reservoir environments[1-3].

Waterflooding has been successfully used for many years in the recovery of oil from petroleum reservoirs. Successful waterfloods often recover as much or more oil than in the primary recovery phase. In spite of the many successes, waterfloods have not always been effective from a technical and/or economic basis. Common problems have included reservoir heterogeneities that cause the channeling of water; low permeability which limits the rate at which water can be injected below the fracture-parting pressure into the reservoir, and high infrastructure costs for applications in reservoirs that are deeper or located offshore.

The concept of horizontal waterflooding was introduced by Taber[4] in 1992 as a method for improving the performance of conventional waterfloods. It was pointed out that water can be injected at much higher rates and lower pressures in horizontal wells than in vertical wells, allowing oil to be recovered quicker. It was further concluded that areal sweep efficiency would be improved by the line-drive geometry as compared to the sweep patterns that develop between vertical wells. Because of the accelerated rate of recovery and the potential for increased total recovery, it was speculated that horizontal waterflooding could offer significant benefits over conventional waterflooding. Joshi was also a pioneer in the development and application of horizontal well technology[5] and recently provided an analysis of the costs and benefits of horizontal wells used in a variety of applications, including waterflooding and enhanced oil recovery[6].

Grand continues to monitor and take advantage of the ongoing industry advancements that have been made. This discussion will show that Grand has advanced the technology during the process of implementing a number of projects. Fig. 1 shows the location of the projects discussed in this paper.

Discussion

Industry Trends.

Horizontal waterflooding has been under development for the past 15 years. Texaco has been a leader in the testing of the technology with applications in the New Hope Field (Texas)[7,8], Aneth Field (Utah)[9,10], and the Captain Field (North Sea)[11]. Table 1 provides the descriptions and applications of the major projects that have been conducted.

In a horizontal well, the curve is referred to as the heel while the end of the lateral is referred to as the toe. A horizontal waterflood, as originally conceived, consists of at least one horizontal injection well and one or more adjacent, parallel horizontal producing wells, heels and toes in the same orientation, as shown in Fig. 2a. With time, the concept of horizontal waterflooding has been expanded to include various combinations of horizontal and vertical wells, depending upon the particular application. In flooding applications, horizontal wells are aligned parallel to the principal orientation of natural fractures so that oil can be mobilized and produced from the matrix. This is in contrast to many primary recovery operations in which the horizontal laterals intersect the natural fractures to maximize productivity.

Field Applications.

The major objective in the earlier applications was to use horizontal wells to improve waterflood performance in deeper, low permeability reservoirs. The low matrix permeability mandated the use of smaller well patterns to recover the oil within a reasonable time frame. At the same time, the cost of drilling the deeper wells was too high to justify their use. Several field tests established that one horizontal well in such a reservoir could replace several vertical wells in effectiveness, with a considerable savings in drilling costs. Good examples are the Texaco projects conducted in the New Hope Shallow Unit[7,8] and the Aneth Field[9,10].

Horizontal waterflooding has also been applied in reservoirs containing moderately viscous oil. This process accelerates and increases oil recovery by the improvement of sweep efficiency and was successfully applied by Texaco in the Captain Field, located in the North Sea[11]. Fig. 3 depicts the theoretical improvement in sweep efficiency achieved by horizontal wells[12]. As shown, the predicted breakthrough volumetric sweep for a conventional 5-spot waterflood is 72% pore volume for a mobility ratio of 1, compared to 83% pore volume for a horizontal waterflood. This higher sweep efficiency predicts that a larger amount of oil can be recovered within the normal life of a project.

Grand focused its early attention on the application of horizontal waterflooding in the 25-50 millidarcy (md) permeability portion of the shallow Bartlesville formation[1-3]. Conventional waterfloods had often failed because of the inability to inject water at sufficient rates while staying below the fracture-parting pressure. By contrast, sufficient volumes of water can be injected below fracture-parting pressure into horizontal injection wells. Horizontal producing wells are then used to capture the mobilized oil. The University of Tulsa, together with the DOE, also designed a similar project in the Glenn Pool Field in Oklahoma[13].

Recent laboratory studies and field projects evaluated the immiscible water-alternating-gas (WAG) process using horizontal wells in reservoirs containing moderately viscous oil. Key targets were the heavier oil reservoirs in the North Slope of Alaska. A recent DOE study estimates that 10-20 billion barrels of moderately heavy oil are contained in reservoirs such as Ugnu, West Sak, and Shrader Bluff[14]. British Petroleum (BP) is evaluating an immiscible WAG process using horizontal wells as a means of recovering a portion of the moderately viscous oils in the North Slope[15]. Horizontal injection wells will permit the high-rate injection of fluids into the reservoir and horizontal producing wells will capture the oil. A soluble gas such as carbon dioxide (CO_2) will dissolve in the heavier oil and reduce its viscosity. The combined effects will permit the recovery of oil that may not otherwise be possible. Thermal projects are not applicable due to the permafrost conditions.

Horizontal injection and producing wells are also being used in low permeability reservoirs where miscible gas flooding is underway. These miscible gas projects are conducted in light oil reservoirs where miscibility with the crude oil can be established with the injection of gasses such as CO_2 or an enriched hydrocarbon gas. Mobil used horizontal injection wells as an alternative to infill drilling in a CO_2 project in the Levelland Field[16]. Mobil also reported plans to use a CO_2 horizontal flooding process in the Aneth Field to improve the economics of the project[17]. EnCana (formerly PanCanadian) used a combination of vertical and horizontal wells to maximize the performance of a CO_2 flood in the Weyburn Field, Canada[18]. Phillips evaluated horizontal injection wells to accelerate the recovery of oil from the South Cowden Unit and to permit the centralization of field handling facilities[19]. ARCO used a combination of vertical and horizontal wells in the implementation of an enriched gas drive project in Prudhoe Bay[20].

Well Patterns.

Experience has shown that the pressure drop through a horizontal injector can be significant relative to the pressure drop between wells within the reservoir. Vicente[21] performed a numerical model study to couple the well flow dynamics of the horizontal wellbore and the reservoir, determining that reservoir models need to incorporate the effects of pressure drop through the horizontal lateral and the transient saturation effects that occur in the reservoir around the wellbore. Steady state models are considered appropriate in low-permeability reservoirs where the pressure drop through the lateral is negligible compared to the pressure drop between wells. In other situations, the reservoir model needs to include a wellbore model along with local grid refinement around the lateral to accurately predict fluid flow through the reservoir. In such cases, there is a tendency for fluids to flow from the heel of a horizontal injector toward the heel of a horizontal producing well. The net result is a lower sweep efficiency and recovery than might be anticipated. Various investigators have studied the problem of non-uniform flow out of and into horizontal laterals and have made recommendations on completions and well configurations that would minimize the problem. Key findings include:

- Lach[11] discusses the use of a “tuned” liner to encourage the distribution of injected water toward the toe of the injection well. A combination of interspersed open wire wrapped screen and blank casing was used to promote a more even inflow profile.

- Popa[22] proposed the drilling of horizontal injectors and producers in a toe-to-heel (TTH) orientation, as shown in Fig. 2b, to promote better sweep between wells. He also proposed the use of horizontal producing wells along with vertical injection wells, pointing out that much better control on flow distribution can be achieved in vertical injection wells rather than in horizontal injection wells. A vertical injection well aligned with the toe(s) of horizontal producing well(s) is also considered TTH and is shown in Fig. 2c-1.

- In a later publication, Popa[23] continues to advocate the drilling of horizontal injectors and producers in a TTH configuration. He further discusses a variety of other field patterns designed to enhance sweep efficiency, noting that horizontal producers are always recommended and that the injectors should be either a vertical well or a relatively short horizontal well, as shown in Fig. 2d.

- Zhao[24] proposes a toe-to-heel waterflooding process to recover heavier oils, in a pattern that utilizes a horizontal producer and a vertical injector. The horizontal producers are located at the top of the formation and the vertical injection well is placed near the toes in a staggered line drive configuration, as shown in Fig. 2c-2. The injected water tends to flow near the bottom of the formation by gravity drainage and the pressure support pushes the oil upward toward the horizontal producing well.

Technical Approach.

Grand has made continuous improvement over the past four years in the development of the technology needed for the successful application of horizontal wells in waterflooding. This success is attributed to the technical team and to innovations in the technology.

Screening of Prospective Reservoirs.

Grand uses a team of professionals to make an initial evaluation of a prospective reservoir as a candidate for horizontal waterflooding. This team consists of a geologist, rock mechanics expert, reservoir engineer, and drilling engineer.

Geologic studies focus on the vertical and areal distribution of porosity and permeability. Isopach, structure, and stratigraphic maps are generated to determine the suitability of a prospect for waterflooding and the use of horizontal wells. The reservoir needs to have lateral continuity, sufficient vertical permeability to permit the use of horizontal wells, and sufficient oil saturation to permit an economic application.

A rock mechanics analysis is performed to evaluate the properties of the rock where the curve and the horizontal lateral will be drilled. This evaluation will determine if the rock has adequate strength to maintain hole stability during drilling and to permit the openhole completion of the lateral. A cased hole completion or liner may be required if borehole stability is an issue.

A reservoir engineering evaluation is made to determine if the prospective reservoir appears suitable based upon prior experiences.

The drilling engineer makes an assessment of all of the issues related to the drilling, logging, and completion of the well. He also evaluates drilling the well underbalanced, to help minimize formation damage.

Approximately 70% of projects do not pass the initial screening and those that do move on to a more rigorous screening process.

Detailed Planning.

The same team of professionals performs the detailed analysis of those potential projects that passed the initial screening.

A major activity during this stage is the use of a 3-dimensional, 3-phase black oil simulator to confirm the suitability and to assist in the design of the project. A reservoir description is initially built into the model by using the previously generated geologic description and by history matching past performance. Once a history match is achieved, a number of simulations are performed to evaluate the impact of different horizontal well design parameters. These include the placement of horizontal and/or vertical wells, the lengths of horizontal laterals, spacing between wells, placement within the vertical interval, and the orientation of wells. Economic analyses are performed on the proposed pattern to be used in the project to confirm viability.

A large number of simulations performed under a variety of conditions have resulted in some general observations. These include: (1) horizontal injection and producing wells should be drilled in a toe-to-heel orientation, (2) horizontal well patterns should be drilled parallel to the prevailing natural fracture orientation in waterflooding operations, (3) horizontal producers should be placed near the top of the reservoir where the oil saturation is the highest, (4) pressure support is needed to sustain production from a horizontal producing well, (5) horizontal injectors should be placed lower within the section, and (6) vertical injection wells are sufficient where good injectivity is possible.

A detailed well plan is developed to specify the kick off point, end of curve, trajectory, orientation, and length of the horizontal wells to be used in the project.

Drilling.

Grand uses a low-cost, rotary-steerable drilling system to drill the short-radius curves discussed in this paper. This system was developed and licensed by Amoco Production Company (now BP). Grand has advanced the technology as a result of drilling these projects.

All existing wells in a prospective project area are reviewed for possible use. If the risk-weighted cost of exiting a candidate well exceeds the cost of a new well, which occurs frequently in this shallow production region, a new well is drilled.

When a new well is required, outside contractors are used to drill and cement casing in the vertical hole to a specified depth. In some cases, the vertical portion of the well is initially drilled through the target formation for the purpose of obtaining additional information about the reservoir. Openhole well logs and a borehole televiewer can be run to evaluate formation characteristics, porosity, fluid saturations, and fracture orientation. In these instances, the well is then plugged back with cement and the horizontal lateral kicked off in an orientation parallel to the observed natural fractures.

There are two drilling assemblies used to drill a horizontal well: the curve drilling assembly (CDA) and the lateral drilling assembly. A gyroscopic surveying tool is utilized to orient the CDA, which drills a reliable curve based upon the tool configuration, typically a 70 ft turning radius. This means that the wells go from vertical to horizontal, 90 degrees, in 70 ft of true vertical depth (TVD), a total drilled length of approximately 110 ft. The curve is typically drilled with water or mud. The CDA is pulled from the hole after the curve has been completed.

A modified air hammer drilling assembly, which produces a good penetration rate, is run into the hole to drill the horizontal lateral to the desired length. An air/foam mixture is used for circulation to permit underbalanced drilling, thereby minimizing formation damage. Precautions are taken to avoid the use of surfactants that tend to emulsify with the oil, which can also cause formation damage. Surveys are run frequently to confirm that the wellbore direction and inclination are within plan. While lengths of up to 1000 ft have been drilled, experience has shown it is not the length of the lateral but how many compartments of high oil saturation are encountered that determine the potential production from the well.

A geologist is on site during the drilling of the well. He analyzes the cuttings from the well and provides an interpretation of the lithology, sand quality, and the presence of oil. Observation of fluids circulated to the pit also provides valuable information on the contents of the reservoir being drilled. Attention is given to the first fluids to the surface after surveying, which acts as a mini drill stem test (DST), as the reservoir has had approximately one hour to fill the wellbore with natural fluids.

Formation Evaluation.

Because conventional well logging tools will not pass through the short radius curve, Grand has developed a procedure to log short radius horizontal wells. Logging tools were modified and are conveyed by conventional sucker rods. Because friction limits the distance to which the logging tools can be pushed with sucker rods only, roller rod guides are used, when necessary, to move the logging tools to a longer distance. This equipment facilitates the acquisition of a suite of logs, including gamma ray, density, induction, and acoustic borehole televiewer for fracture identification.

Completion.

Because of the short-radius of the curve, it is possible to use a conventional downhole pump assembly, set in the vertical section above the curve, with relatively low pressure head on the formation. The initial production provides an early indicator of the amounts of oil, water, and gas that will be produced from the well. It has been noted that there is a good correlation between the amount of oil circulated to the pit during drilling and the stabilized oil production rate that is ultimately achieved from the well. The curve and horizontal portions of the well are openhole completed, with no stimulation required.