APPLICATIONS OF FISHBONE DRILLING

A PROJECT REPORT

Submitted by

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CERTIFICATE OF COMPLETITION

This is to certify that Mr.Akshay K K, final year student of B.Tech Petroleum Engineering, Global Institute of Engineering & Technology, Vellore has completed his Internal Project on “Application of Fishbone Drilling”

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Head of Department

Petroleum Engineering

GIT

ACKNOWLEDGEMENT

The success and final outcome of this project required a lot of guidance and assistance from people and we extremely fortunate to have got this all along the completion of my work whatever we have done only due to such guidance and help and we would not forgot to thank them.

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I wish to express our sincere thanks to our guide **Mr. JARRAR AHMED,** AEE(R) **ONGC –** Cauvery Asset, Neravy, Karaikal – 609 604

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AKSHAY K K

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Chapter 1

ONGC-CAUVERY ASSET

1.1 INTRODUCTION TO GEOLOGY OF CAUVERY BASIN

On the east coast of Southern India, in the state Tamil Nadu, of large alluvium covered coastal belt along Coromandel coast including Gulf of Mannar, Palk Bay forms the Cauvery basin (Fig.1). The basin encompasses a total area of around 62,500sq.km up to a bathymetry of 200m in the Bay of Bengal. The basin is roughly 100 to 150 km wide in E-W direction and 400 km long in N-S direction. The basin evolved as a composite of rifted graben since Late Jurassic and formed a part in the development of East Coast divergent margin of India. Towards eastern margin of the basin few isolated outcrops of Mesozoic and Tertiary sedimentary rocks are seen near Sivaganga, Ariyalur, and Vrudhachalam and Pondicherry areas. The exposed sedimentary rocks along western margin prompted the Geoscientists of ONGC to initiate exploration in 1958 followed by geophysical surveys in 1960.

Twenty years of active exploration has led to the drilling and finding of non-commercial oil strike in 1977 (Karaikal # 10). However, enormous amount of data generated during this period warranted restudy and reinterpretation, a drilling holiday was thus declared between 1977 and 1984. Second phase of drilling commenced in 1984. The next year itself has led to the discovery of two important fields Narimanam and Kovilkalappal. Since then ONGC has never looked back in its exploratory efforts in finding oil and gas fields, across the basin.

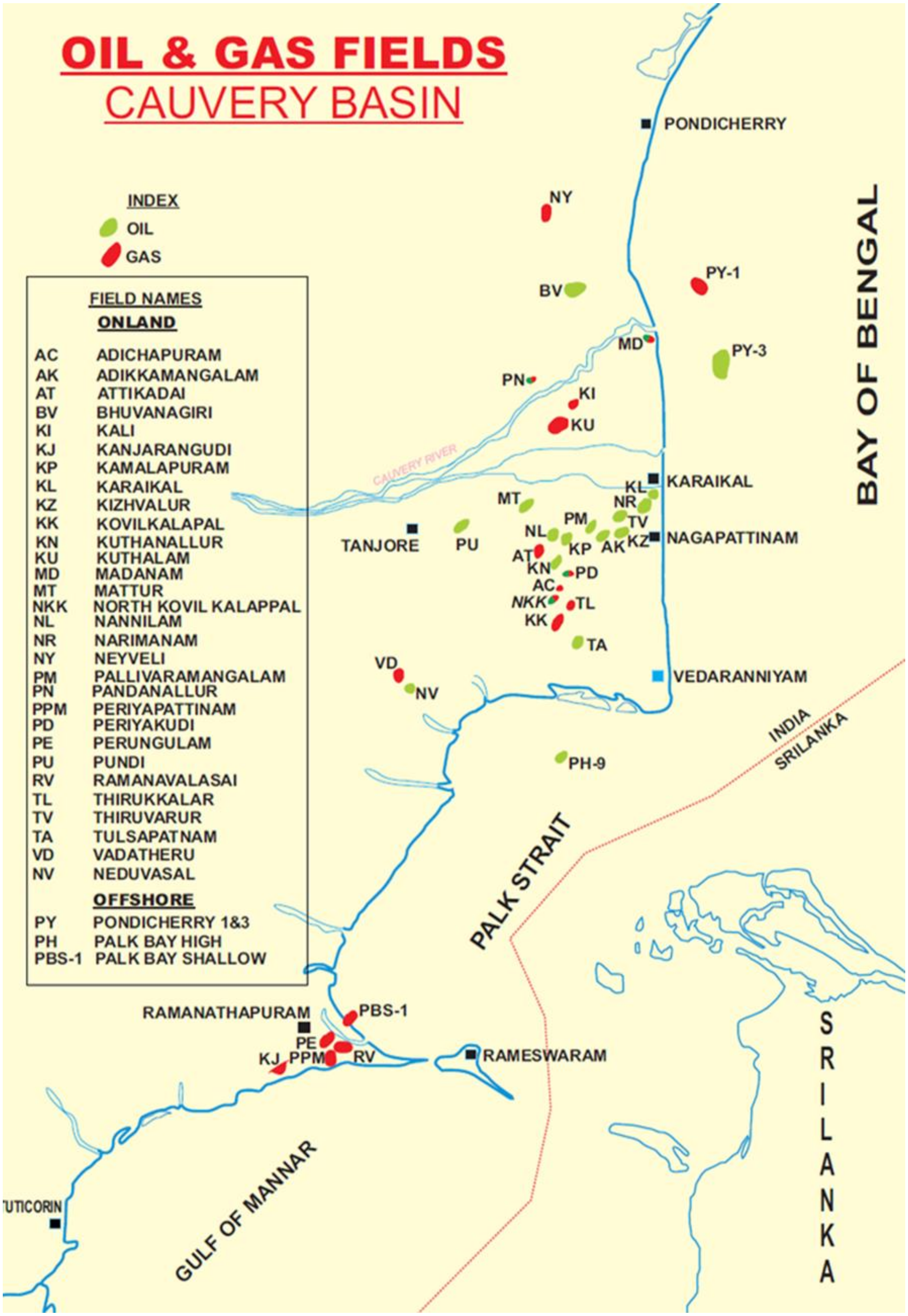
1.2 INTODUCTION TO CAUVERY ASSET

The Oil and Gas exploration giant ONGC occupies a pride of place among India’s Maharatna Companies. Within ONGC, the 'Cauvery Asset', hub of Production and Development activities in the remote Southern most parts of India is one of the success stories in its relentless pursuit of oil and gas. Cauvery Asset is based at Karaikal. ONGC's presence in this region has given a boost to Industrial Development in the districts of Nagapattinam, Karaikal, Tiruvarur, Ramnadu and Cuddalore. The mushrooming of Steel Units, Power Generation Stations, and ceramic industries in these areas bear testimony to this. Private and Public Sector power generation stations operate on gas supplied from ONGC's oil and gas fields. A number of private players apart from TNEB have set up gas-based power projects in this area, using gas from ONGC generating more than 800 MW power. A further feather in the cap for the Cauvery Asset is the sale of Sour gas from Narimanam and Kovilkalappal fields. The Cauvery Basin covers an area of about 25000 sq.km in the Onshore and extends from Puducherry in the North to Ramnad in the South and Thanjavur in the West to Karaikal in the East. Intense geological processes taking place beneath the sands of this Cauvery Basin have made it the home for the Hydrocarbons. Hydrocarbons in the form of oil and gas are found in reservoir pockets distributed all over this vast basin. The basin is under active exploration and development of oil and gas pools with the deployment of nine drilling rigs and four workover rigs dedicated to the revival of sick wells. The main constraint in this basin is that there are multiple thin layers of Sand hosting the Reservoirs rather than thick Blanket Sands, such as encountered in the Assam Shelf which lend themselves to Reservoir mapping and Interpretation more easily, thus facilitating Development activities. Cauvery Basin has much smaller oil and gas pools.

1.3 EXPLORATION

ONGC's exploration activities in Cauvery Basin started nearly fifty years ago, in 1958 to be precise. The exposed sedimentary rocks along the western fringe of the basin prompted the geoscientists of ONGC to initiate exploration for Hydrocarbons. Drilling began in 1964 and the first taste of success came with the finding of oil in the well 'Karaikal # 10' in 1977. Twenty years of active exploration had yielded copious geo-scientific data. Immediately after this, in order to review and reinterpret the findings, a drilling holiday was declared in 1977. After a detailed review of all available data, the second phase of drilling commenced in 1984. Success greeted the dedicated workforce of ONGC, almost immediately, with the discovery of Kovilkalappal and Narimanam fields, in 1985. Cauvery Basin had emerged on the oil map of the country.

This major breakthrough brought the basin into exploratory focus. The rejuvenated exploratory efforts resulted in drilling 618 wells as on 01.02.2012 out of which 144 are oil and 96 are gas wells. This has led to the discovery of 29 oil and gas fields, the milestones of this basin. They are: Karaikal (1977), Kovilkalappal (1988), Adiyakkamangalam (1989), Kamalapuram and Tiruvarur (1990), Mattur, Athikadai, Vadatheru and Vijayapuram (1992), Pallivaramangalam and Kuttanallur(1993), Perungulam (1994), Pundi (1995), Kizhvalur and Kuthalam (1996), Tulsiapatnam, Periyapatnam, Neyveli and Ramanvalasai (1997) and Kali (1998), Kuthalam satellite fields (1999), Kanjirangudi (2000), Palk Bay Shallow-Offshore (2001), Adichapuram (2007), Periyakudi(2010), Madanam&Pandanallur (2012)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RAMESWARAM
SRILANKA
GULF OF MANNAR
TUTICORIN

Well Status as on 01.12.2018	
Wells Drilled	712
Exploratory	530
Development	182
Flowing	83(Oil) + 87(Gas) = 170
Non-Flowing	82(Oil) + 47(Gas) = 129
Inconclusive	7
Abandoned	391

Status of Exploration

On land Offshore

Area (Sq.Km)	25,000	30,000
Prognosticated Resources	430	270
Prospects Drilled	150	34
Oil & Gas bearing	26	3
Success ratio (Prospects)	1:5.76	1:11.33

Chapter 2

INTRODUCTION TO FISHBONE DRILLING

A horizontal well drilled with a multilateral fishbone shape to increase production. This type of drilling, in which branches (ribs) are drilled into a single layer from the main horizontal section, increases the reservoir drainage area over that covered by single-bore horizontal wells.

Radial jet drilling was invented in the1980's and has been used on thousands of wells worldwide since then .It is a low-cost method to drill numerous, small-diameter horizontal laterals from an existing wellbore. When incorporated into a horizontal well, the resulting architecture is sometimes called a "fish bones".

The mathematical models for the number of branches of the thin layer fish bones well, the branch borehole length, branch angle and distance between the branch borehole system optimization model have been established. Some key issues such as safe separation between the main borehole and the branch borehole, Interlayer wall construction method of the unconsolidated strata,drilling string and completion string trip-in have been solved. A suit of technology such as open hole sidetracking technology, Interlayer wall construction method of the unconsolidated strata and drilling string and completion string trip-in technology have been formed. Through integrated application of geological-oriented drilling, composite drilling, trajectory control, open hole sidetracking technique and other supporting technologies, have completed two wells on-site testing. Technical problems such as go across the ultra-thin oil layer, branched hole three dimensional Pressurize and evaluation of drilling tool throughput capacity have been solved successfully. We achieved in drilling branch in 1.5 m thickness of the reservoir. It is currently the thinnest oil drilling fishbone wells

The early production of the two test fish bone wells has reached 10 times to the conterminous well, stable output is 3.5 times, Its effect is significant. Fishbone well Technology put the Single path horizontal section plane extends to more than one horizontal wellbore. Achieved more expose reservoir and increased the well production, providing an effective approach for economic development of low permeability, low abundance and thin low-yielding oil field reservoir.

2.1 FISHBONE WELLS

Fishbone Wells are series of multilateral segments that fall into a horizontal well. They are called so because they look like the ribs of the skeleton fish. A Fishbone stimulation system is ideally used in onshore low permeability tight gas reservoirs. The vertical branches make vertical flow path which is similar to hydraulic fracturing. They are open hole liners that link the well with the reservoir and perform all fishbone operations. For instance, circulating the fluids with the rig pumps and setting the liner hanger slips become easy with the help of a fishbone stimulation system.

Fishbone wells are one of the most effective ways used to improve the production rate of wells. The design of the wells is a complex process as it focuses on the optimization of branch length, branch number, and branch angle. The process is an effective method for economic development at low permeability, low yielding oil reservoirs, and low abundance. Some advantages of the wells include:

- Larger drainage area and high single well production rate can be obtained, compared with conventional horizontal well.
- The layers can be effectively connected to reduce the economic risk in heterogeneity stratum, which improved development benefits in low permeability reservoir.
- The single well engineering cost can be reduced, such as drilling operation, land, rig transportation, rig up, rig down, casing, cementing, drilling fluid, waste mud and cuttings dispose, etc. Further more, the cost of surface oil production and transportation are decreased.

Moreover, Fishbone wells can generate a net present value similar to fractured wells and their productivity does not decline over time.

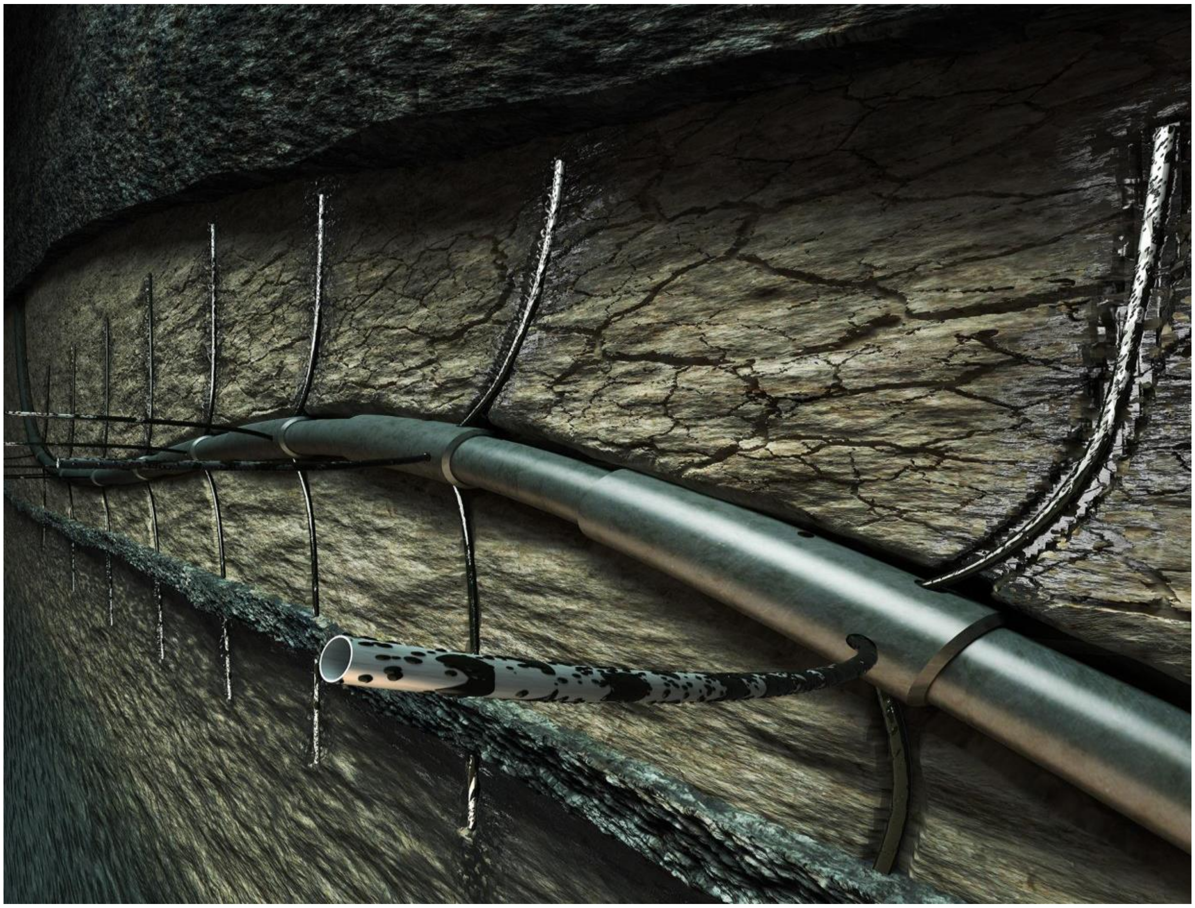


figure-1.fishbone well

2.2 OBJECTIVE OF FISHBONE DRILLING

Fishbone drilling plays a central role in the successful development of hydrocarbon production. The fishbone wells are new production technology applied to increase well productivity and access the difficult geological formations and unconventional reservoirs. The main advantages of this technology over hydraulic fracturing are the competitive price and reduced operation time.

- **Increase productivity** by connecting the well to the reservoir with up to 300 laterals.
- **Accelerate production** by integrating stimulation in your drilling program.
- **Avoid water or unwanted gas** by predictable penetration and location of the laterals.

- **Simplify logistics** by using rig pumps and significantly less fluids.
- **Accelerate progress** by avoiding cementing, perforating, cleanouts, running frac strings and other operations.
- **Reduce HSE exposure** by reducing the number of operations and man-hours. Reduce the environmental impact by reducing emissions and by using less fluids.
- **Avoid flow back** and disposal of fluid from hydraulic fracturing.
- **Effective reservoir conductivity** may be low due to layering or faulting. The layers or faults can be penetrated and drained by Fishbones with the mother bore not even penetrating the faults.
- **Different intervals have different pressures** and can be hard to effectively hydraulically stimulate. Fishbones allows you to stimulate zones with different pressure regimes.

In many cases, carbonate oil wells are stimulated by acidizing methods which can be inaccurate, inefficient, and otherwise complicated. The results of acid flushes and acid fracturing can vary widely making interpretation and repeatability difficult. A new stimulation solution has been developed to be simple, efficient, and accurate in using acid to create laterals into the formation, making contact with existing natural fractures and bypassing formation damage. The Fishbones system is installed as a part of a liner string into drilled reservoir section. Fishbones subs are spaced out to target specific parts of the reservoir and each sub contains four small diameter tubes with length up to 40 feet. A typical acidizing fluid system is utilized and when pumped fluid jets of out nozzles at the end of each tube. The formation ahead of the tubes is jetted away with a combination of erosion and acid chemical reaction. Differential pressure across the liner drives the tubes into the formation penetrating the rock until fully extended. All laterals are created simultaneously in a short pumping job, resulting in a fishbone style well completion with multiple laterals extending from the mainbore. The liner with the extended tubes becomes a permanent completion with included production valves, which allow flow to enter the new system called Dreamliner multilateral well stimulation (MST) is an open hole liner completion that essentially creates a network of routes in a reservoir that connects them to the well, increasing connectivity and productivity.

HOW IT WORKS

The Dreamliner system is installed as part of a liner sub that houses small, high strength titanium tubes called needles to jet out into the formation, which is positioned across the formation where the well needs stimulating. Each needle is 40ft-long, has a jet nozzle on the end and is driven by a turbine. During the jetting process, a small lateral is created, which connects up the existing fracture network.

Stimulation is performed on oil and gas wells to increase production by improving the flow of the hydrocarbon resource. Sometimes a well has low permeability, so stimulation by acid, petroleum or steam is required to make the rock more porous so to initiate production from a reservoir. Stimulation is also used when permeability and flow from an already existing well needs to be encouraged if it has become under-productive.

2.3 HISTORY OF FISHBONE DRILLING

2.3.1 AN OVERVIEW

- Back in 2013, a Fishbones stimulation system was installed for the first time. The project took place in a coal field in South Sumatra to investigate its resource potential. A 800m-deep, vertical well was drilled with a 180m-wide open hole.
- In 2014, the Fishbone's(sevice provider) MST was successfully deployed in the tight Austin Chalk formation in Texas and 30 days later the company reported that the well was producing better than ever before. Production was increased by over eight times and the productivity index increased by 30 times.
- The liner-based stimulation technology was originally developed for carbonate reserves (sedimentary rocks). Experience in the field has shown that the Dreamliner MST has proven to be successful in both tight limestone formation and carbonate reservoirs.
- For example, in July 2015, Fishbones Dreamliner MST was successfully installed in a new, horizontal well in a sandstone formation in the Norwegian Sea. The sand formation had low permeability, so the reserves were

previously considered non-economical to develop to access the gas reservoir underneath. The Fishbones system could be the solution to this.

2.3.2 CASE STUDY OF VANKOR FIELD

JSC “Vankorneft”, a subsidiary of Russian national oil company “Rosneft”, established in 2004 to operate Vankor oil and gas field - the largest of the fields discovered and put into operation in Russia over the past twenty-five years. The field is located in the Turukhansk District of Krasnoyarsk Krai, on the north of Eastern Siberia. Its total area is 416.5 sq. km. Initial recoverable reserves of Vankor field as of January 1, 2014 is 500 million tons of oil and condensate and 182 billion cubic meters of gas (natural dissolved). In 2013, Vankor field produced 21.4 million tons of oil and gas, which is higher than last year’s result by 17 %. In 2014 daily production (as of 01.01.2014) 9 % increased compared to the same period of 2013 - more than 60 thousand tons. Thanks to technological solutions used the oil recovery rate at Vankor - one of the highest in Russia. The field develops by injection wells, slant wells, and production horizontal wells, to ensure high production rate. According of oil and gas geological zoning system the Vankor field is located within the oil and gas Pur-Taz region as a part of West Siberian oil and gas province. In tectonically the field timed to the Vankor elevation in the northern part of the Lodochnogo wall, complicating the southern part of the Bolshekhetskaya structural terraces Nadym - Taz syncline. Its main productive horizons are sandy composition and timed to lower cretaceous sediments of nizhnehetskoy (upper berriasian - lower valanginian) and yakovlevskoy (middle aptian - middle albian) formations. At the top dolgan formation (upper albian - cenomanian) non-industrial gas accumulation are installed. Section of Yakovlev Formation represented by clays and siltstones, with the interbedded sands at the top and sand packs and sandstone, layers of brown coal up to 2-4 m. As a part of top section of the formation emit up to seven layers of sand. Formation capacity - up to 650 m. Sweet according lies on sandstone malohetskoy formation and covered the Dolgan formation, also folded mainly sands and sandstones . Within Nizhnehetskaya Formation overlie a few productive oil-saturated objects, one layer is Nh1 formation. The average formation thickness is about1–2 meters. Considering the formation evaluation properties of the current layer may be noted a high range of variability of the clay contains in the reservoir rock, which in turn has an impact on permeability of rocks. Within domed portion of the oil-saturated reservoir, mainly represented by good formation properties. On Vankor oilfield, drilling of conventional long horizontal wells in the given formation allow efficient and evenly recoverable hydrocarbon reserves. Looking at arched of the developed object, reservoir properties is significantly deteriorated by increasing of the clay material in the reservoir rock, thereby greatly understating permeability and productivity of formation. In this case, the efficiency of drilling conventional horizontal wells in the current areas, is questionable and perhaps even are economically disadvantageous in view of significant drop of production rate. Earlier the operator company has conducted measures to increase the flow in the low filtration formation, using technology of hydraulic fracturing, but without success. The failure was that after fracturing rapid watering wells, even though that within the experimental horizontal wells underlying aquifer is absent, and, as a whole, thin productive reservoir is located between two packs of impermeable shale formation on the top and on the bottom. Reasons of watering has not yet been established. As a result of consideration positive and negative aspects of the drilling technology horizontal multilateral wells, their economic feasibility, the degree of impact to the productive formation and the prospects for long-term production level, “VankorNeft” proposed to drill a fishbone shape well with nine branches drilling out from the main trunk along horizontal section. According to geological conditions, the main significant challenge is to place “bones” in narrow drilling tunnel 1m above and 1m below trajectory. Upon completion of construction, well completion planned run liner in the main trunk, branches still uncased.

2.3.3 Multilateral wells concept

Multilateral wells are characterized according to definitions established in the Technical Advancement of Multilaterals (TAML) Forum held in Aberdeen, Scotland, July 26, 1999 and recently updated in a July 2 2002 draft proposal. These standards classify junctions as Level 1, 2, 3, 4, 5 or 6 based on degree of mechanical complexity, connectivity and hydraulic isolation (Figure1). The complexity increases with increasing level.

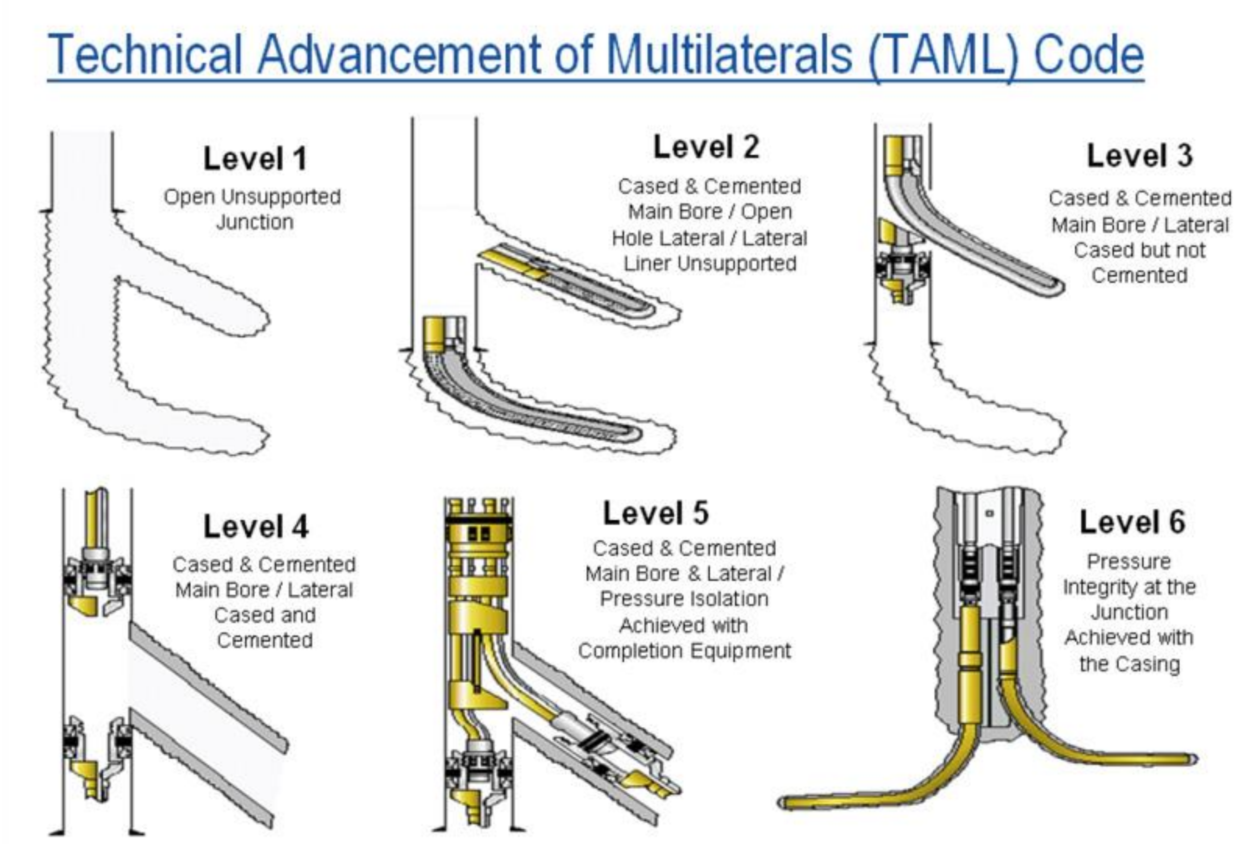


Figure 11—Junction classification

Level 1 – Open unsupported junction Barefoot mother bore and lateral or slotted liner hung-off in either bore.

Level 2 – Mother bore cased and cemented, lateral open Lateral either barefoot or with slotted liner hung-off in open hole.

Level 3 – Mother bore cased and cemented, lateral cased but not cemented Lateral liner anchored to mother bore with a liner hanger but not cemented.

Level 4 – Mother bore and lateral cased and cemented Both bores cemented at the junction.

Level 5 – Pressure integrity at the junction Pressure integrity provided by using straddle packers.

Level 6 – Pressure integrity at the junction Integral mechanical casing seal (cement alone is NOT sufficient).

Includes reformable as well as nonreformable, full – diameter splitter that require larger diameter wellbores.

Multilateral well configurations range from a single drainhole to multiple well branches in horizontalfanned, vertical-stacked or dual-opposed arrangements (Figure 12). Laterals are completed as openholes and with uncemented or cemented “drop-off” liners— casing that is not connected to the main wellbore. Other completion designs use mechanical assemblies to provide a strong connection, pressure integrity and selective access at junctions between lateral liners and the primary casing of a main wellbore. Like any other well completion, multilateral liners often include external casing packers to ensure zonal isolation or mechanical screens for sand control. Production from individual laterals can be commingled or flow to surface through separate tubing strings. Today, wells also may incorporate advanced completion equipment to monitor and control flow from each lateral branch. Accordingly, drilling and completion risks vary with well configuration, junction complexity, well-completion requirements and downhole equipment.

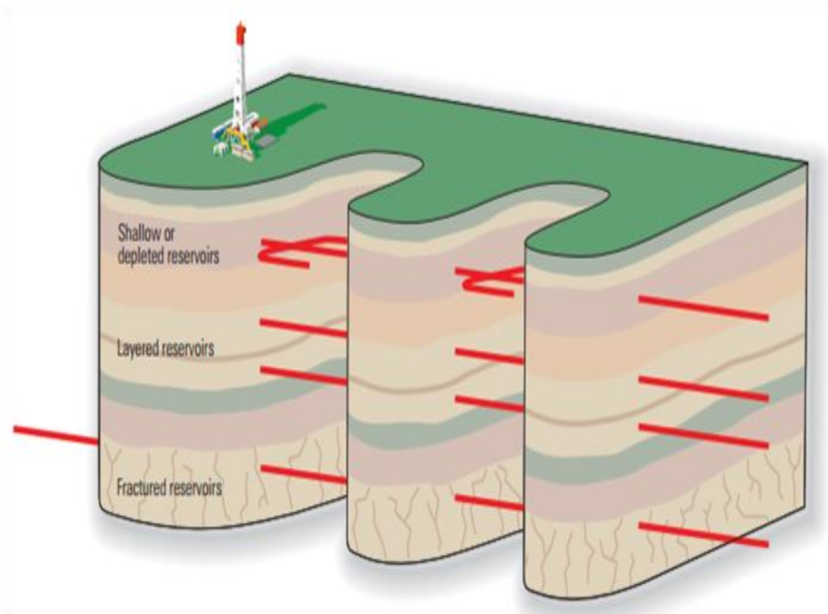


Figure 12—Basic multilateral configurations.

Horizontally spread laterals in fork, fan or spine-rib arrangements target a single zone to maximize production from shallow low-pressure or heavy-oil reservoirs and fields with depleted pressure. Vertically stacked laterals are effective in laminated formations or layered reservoirs; commingling several horizons increases well productivity and improves hydrocarbon recovery

Multiple laterals increase productivity by contacting more reservoir than a single-bore well. In some fields, multilateral technology offers advantages over other completion techniques, such as conventional vertical and horizontal wells or fracture stimulation treatments. Technology of multilateral wells drilling is one of the effective ways to stimulation, allows to provide additional production compared to the traditional horizontal drilling. – Multilateral wells consists of a main trunk and single / multiple branches, drilled within a producing formation. At the same time, unlike the multilateral wells, where each trunk is a separate and fully replacing one well, lateral branches of multilateral wells are usually found on small (up to 200m) away from the main trunk. It should be noted that, if the vertical or directional wells - a spot opening formation, horizontal - linear, the multilateral wells - this is the transition to volumetric methods of oilfield development. – Multilateral wells allow for the same length of the main trunk to increase drainage of the producing formation and provide more productivity in comparison with the horizontal well. Thus, in essence, branches of multilateral wells are analogues of cracks multizone fracturing in horizontal wells. – In contrast to the horizontal wellbore, branches of multilateral wells allow covering a significant Figure 3—Basic multilateral configurations. Horizontally spread laterals in fork, fan or spine-rib arrangements target a single zone to maximize production from shallow low-pressure or heavy-oil reservoirs and fields with depleted pressure. Vertically stacked laterals are effective in laminated formations or layered reservoirs; commingling several horizons increases well productivity and improves hydrocarbon recovery portion of high permeability parts, near main trunk zone, thereby increasing the productivity of the entire well, or be comparable to the horizontal wellbore. Since drilling of this horizontal well was carried out within a production formation Nh1, then the type of multilateral well refers to “fishbone” type. According the junction classification (TAML), this well is assigned to Level 1, where the liner run only in main trunk, laterals stay on uncased. Analysis of elastic-mechanical properties of current formation based on acoustic logging, as well as drilling experience from previous wells in these formations showed that the reservoir rock consolidated enough and did not cause any issues with borehole collapse earlier.

2.3.4 Technology drilling of multilateral fishbone well

On the Vankor field drilled more than 600 wells, with a standard well bore construction design for thisfield. As usual, the length of the horizontal section for wells to Nizhnehetskaya formation is 1000 meters.True Vertical Depth (TVD) of Nh – 1 is 2700 meters. Horizontal section drill by RSS BHA, consist with neutron logging tools, resistivity and natural gamma radiation of rocks, which allows real-time geosteering while drilling.The design of “Fishbone” well is not significantly different from the standard. The main change has been made in the horizontal section: on the top of the formation set 178 mm casing, followed by cementing. Drilling out from casing shoe do by Rotary Steerable System BHA, hereafter “RSS - BHA”and drilling ahead the main trunk, bit OD – 152.4 mm. Drilling of the branches do by Positive Displacement Motor BHA, hereafter “PDM – BHA”, bit OD – 123.8 mm. Branches has different OD from the main trunk in order to avoid entering liner to laterals while running in the hole. The liner construction assumes the shoe on the end with OD – 133 mm. The diameter of the drill bit for the branches has been selected on preliminary agreement. Initially the customer offered a smaller bit 120.8mm, but the optimal size was chosen 123.8 mm to increase the gap between the walls of the borehole and the BHA, which reduce the risk of stuck and for more optimal selection BHA elements (Motor, Telemetry etc.).

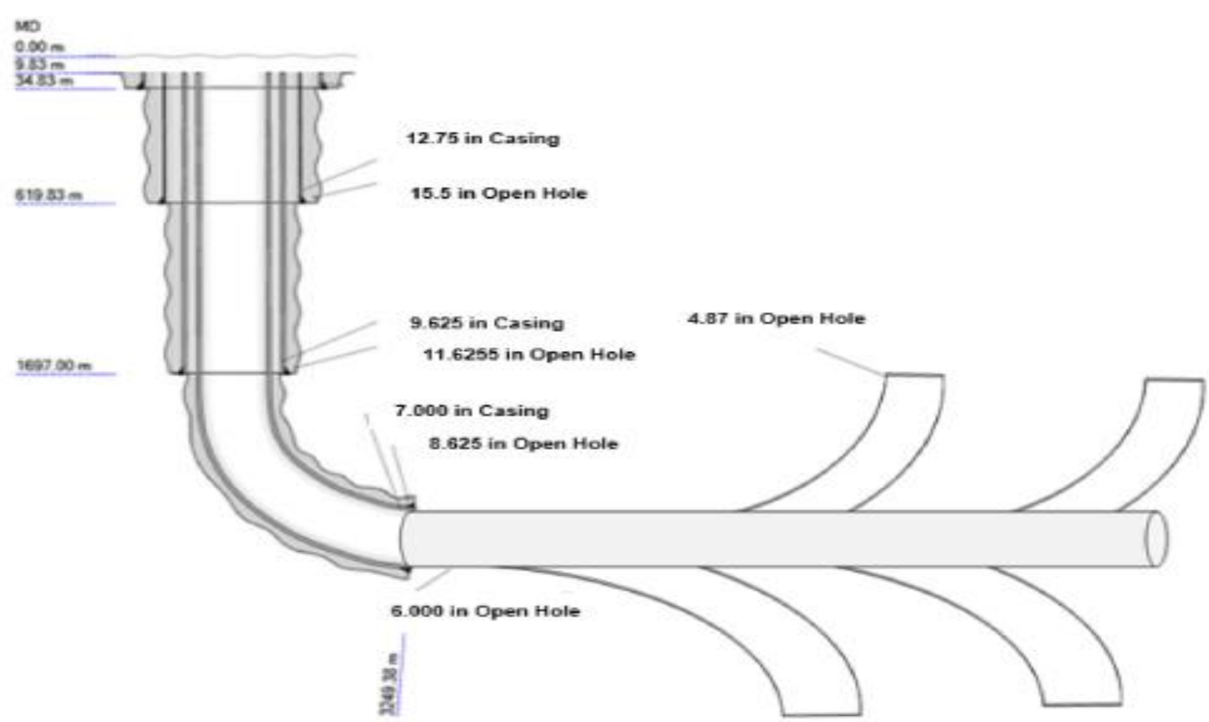


Figure 2—Fishbone Wellbore Geometry

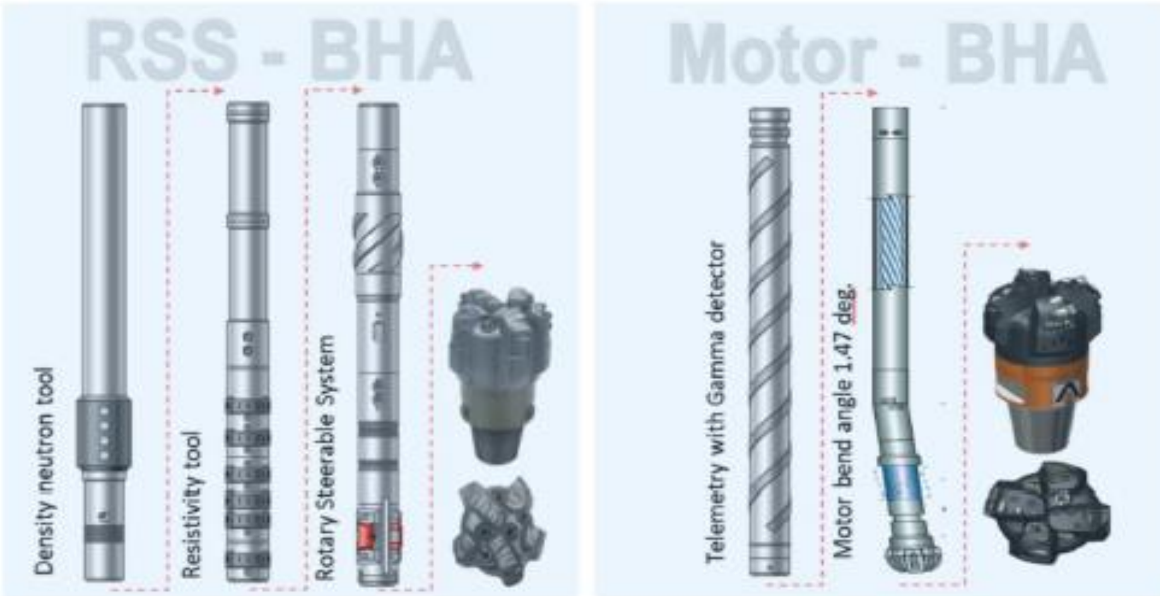


Figure 3—BHA's used to drill horizontal section of fishbone well

At the stage of project approval, through discussion was chosen the optimal branches location within 1000m horizontal section, every 100 m. It was decided to drill laterals alternately in different directions in a staggered manner. Total planned nine branches, length of 150 m each. To maximize departure branches from the "mother bore", planned Dog Leg Severity (DLS) – 14 deg / 30m, most of which falls to turn the azimuth angle.

Drilling sequence was as following:

RSS - BHA

1. Drilling out from casing shoe done by "RSS-BHA" till first kick-off point to Branch # 01
2. Well profile planned to have "ramp" (Figure 4) at specific depth in front of drilling each branch,

which allowed excluding time of "trenching" operation before RSS sidetrack

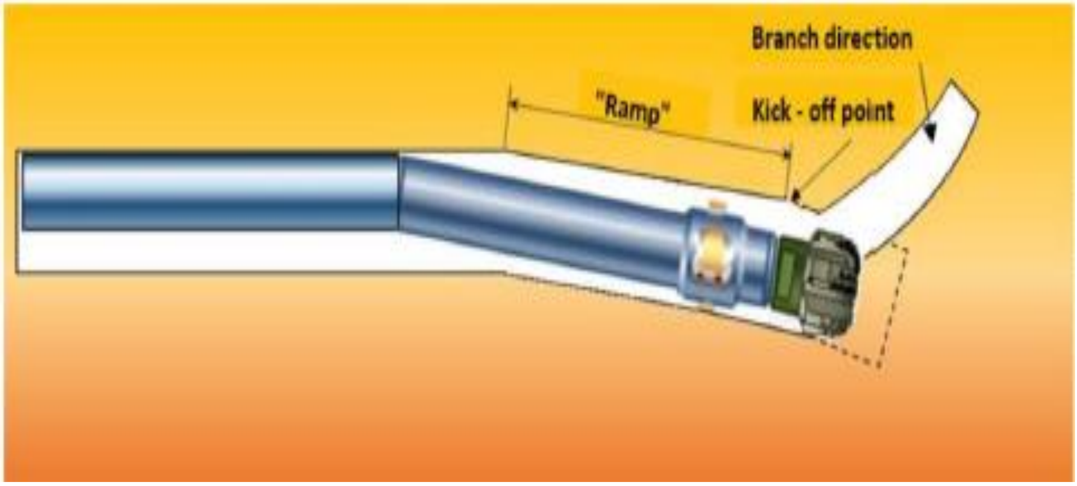


Figure 4—"Ramp" example

3. POOH to change "RSS-BHA" to "Motor-BHA", RIH "Motor-BHA"

Motor - BHA

4 Drill ahead Branch # 01 to TD

5 POOH to change "Motor-BHA" to "RSS-BHA", RIH "RSS-BHA"

RSS – BHA

6 Perform RSS openhole ST (sidetrack) from kick-off point

8 Continue drilling "motherbore" to second kick-off point to Branch #02

8 POOH to change "RSS-BHA" to "Motor-BHA", RIH "Motor-BHA"

Same operations repeated for each subsequent branches

As mentioned above, drilling of the branches planned to drill with bit OD – 123.8 mm, that's why slimhole tools selected to achieve planned DLS. First Branch decided to drill with PDC bit and by results of the run plan to drilling next laterals either PDC or switch to roller cone bit. A potential issue with this BHA was the connection between the SDP 101.6 x 8.38 "S-135" (2 7/8") and SDP 73 x 9.19 "G-105" (4") drill pipes that had an additional force to breaking DP on connection. From D&M side there we suggested client to use 89 mm (3 ½") drillpipe instead of 73 mm (2 7/8"), but in favor of the client choice of the 73 mm (2 7/8") drillpipe has been made in view of its availability on the field. To eliminate additional forces pre run critical loads calculation was performed and were monitoring while drilling. In additional,lubricants concentration were increased up to 3.5% in the mud while drilling laterals. Mud type – WBM,uses on the field on horizontal sections.Selected drilling technology are planning to make nine openhole sidetracks, therefore had the task – to reduce the time spent for kick-off operations. At the planning stage, made time optimization for RSS openhole sidetracks. "Time drilling" as much as possible optimized.

Three options of RSS kick-off operation were offered:

1. "Quick sidetrack" without "trenching" technique. Planned time – 6hr

2. “Quick sidetrack” with “trenching” technique. Planned time – 6-8hr
3. “Conventional sidetrack” Planned time – 24-25hr
All openhole RSS sidetracks performed successfully. All three sidetrack options were applied duringdrilling “fishbone” well (Figure 5).

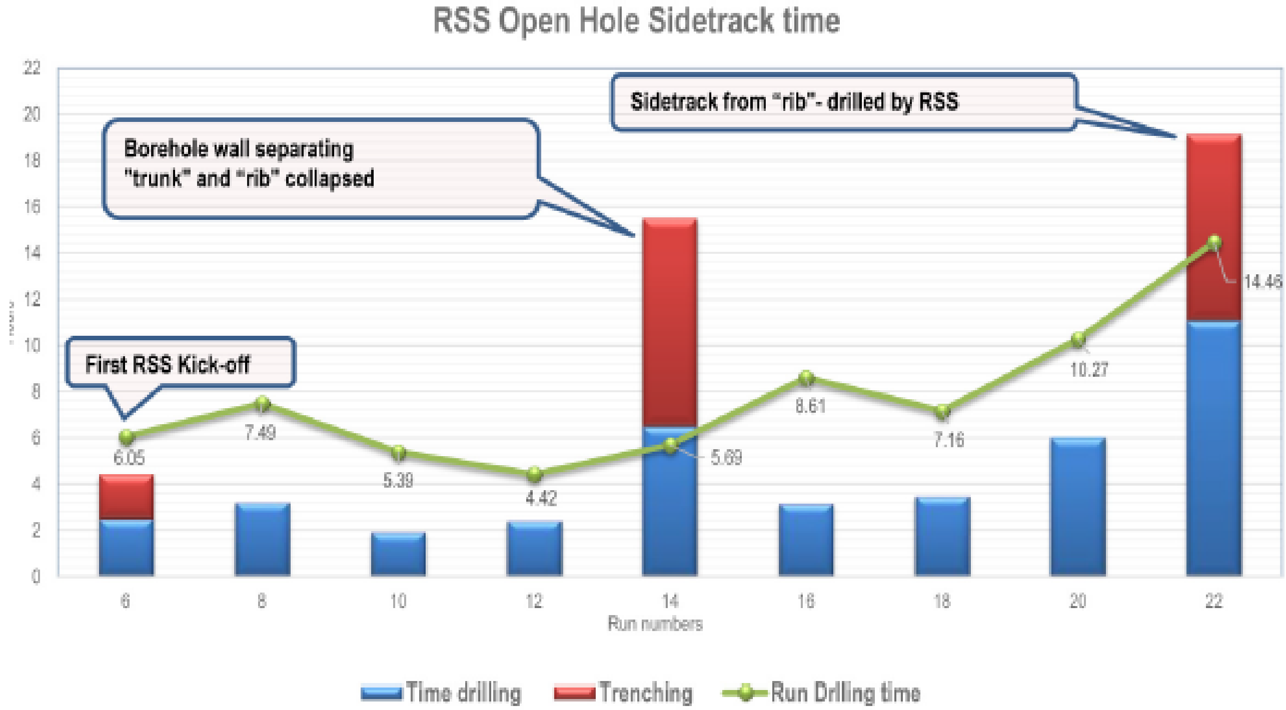


Figure 5—RSS sidetracks performance

First ST executed in accordance to the second option of RSS openhole sidetrack, as good balance between time and success rate. Most of the ST performed by the first option of sidetrack, since the transition between OD of the main trunk and “branches” contributed to the sidetrack success.Difficulties arose during RSS ST from Branch # 05 in Run # 14. ST operation began by the first option as usual. Drilled 2 m in “time-drilling”, increased ROP to 5 m/h and drilled 5 m after downlink. Soon we observed indications of continuous inclination getting into branch back. Possible cause - a change of rocks or cracks on the walls that led to the collapse of the wall between the main trunk and branch. Due to worsening conditions for sidetrack operation, went to third sidetrack option. Sidetrack operation carried out successfully in less time than planned. To avoid recurrence of such situation in the future, it was decided to increase the time of “time-drilling” operation. Even with preventive measures, for sidetracks spent less time than anticipated.Third sidetrack option, “Conventional sidetrack” also was applied on the last sidetrack from Branch #09, since drilling lateral and main trunk performed by the same “RSS - BHA” and there was no transition diameter and high DLS of Branch # 09.During drilling constantly optimizes the time of well construction. One of the successful optimizations- drilling the last Branch # 09 by RSS – BHA, the DLS to turn azimuth of course was less than 14 deg/ 30 m. The maximum turn rate reached 8 deg / 30 m. This rate in such a short section, do not allow moving far enough away from the “main trunk”. To maximize the departure between the branch and main trunk, decided to drill the last segment of the main trunk to counter turn of the azimuth. As a result, the end of the Fishbone looks like a “snake’s tongue” with closure 27 meters.The liner construction is conventional for the Vankor field (Figure 6) had successfully run into the“mother bore”.

Figure 6—Slotted liner construction:

1. Liner shoe 114.3 mm – 4316 m.
2. Slotted screens 114.45 x 30 x 6000 – 127/132 – OTTM interval – 4315.65 – 3293.01 m.
3. Casing OTTM 114.3 x 8.6 “E” interval – 3293.01 – 3204.05 m. (8 pc. – 88.96 m)
4. Liner hanger non-cemented 1. 127 / 178 – 112 / 152 # 286 – 14 – 3203.77 – 3200.35 m.
5. Centralizers – 114/146 – 200 – 4 pc.

Liner head 127 / 178 – 112 / 152 depth 3201.96 m.

Since the last sidetrack # 09 has the same OD (152.4 mm) as the main trunk, to determine to what way liner launched has allowed that main trunk had intentionally drilled 16 meters deeper than sidetrack # 09.

Results

Drilling of horizontal section with nine “bones” performed in 17 according to the plan (Figure 7). All sidetracks done successfully.

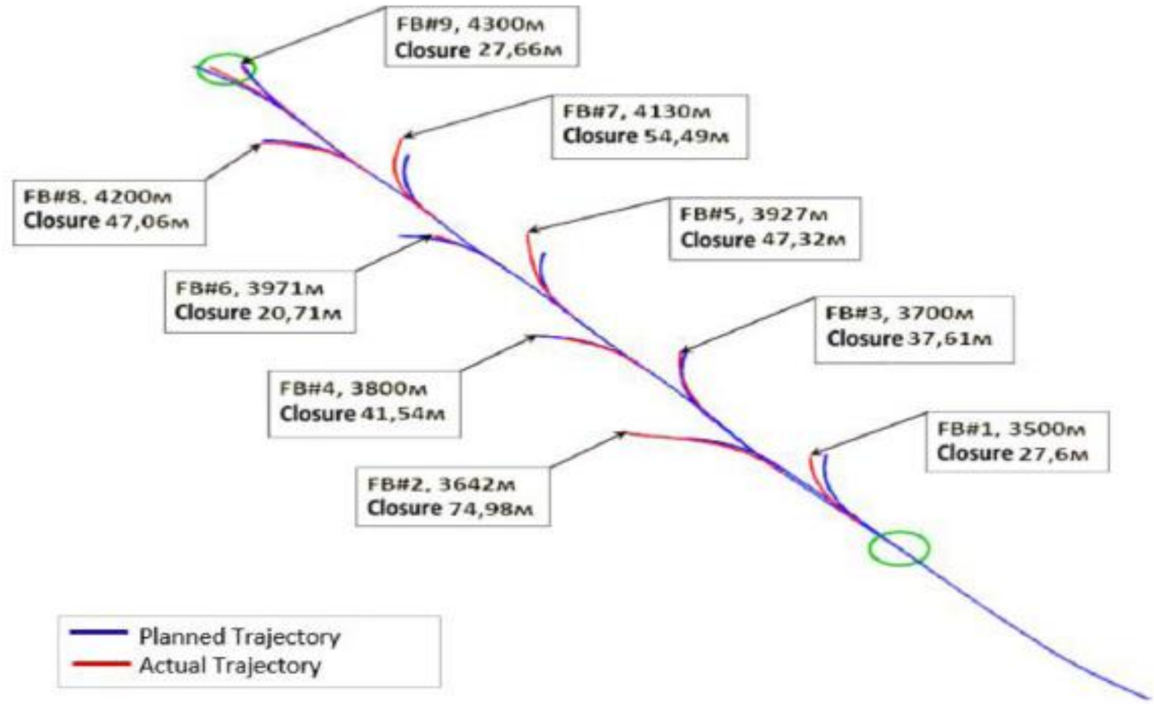


Figure 7—Plan vs Actual trajectory

Drilling time – 115.55 hr.
Circulation time – 341.45 hr.
Average ROP – 19.8 m/hr.
Time spent – 37.7 days.
Horizontal section footage – 2003 m., of them are;
Branches footage – 970 m.
Main trunk footage – 1033 m.
The longest Branch # 02 – 142 m.
The shortest Branch # 06 – 71 m.
All openhole sidetrack done by RSS – BHA.
First successful multilateral well in East Siberia
Record amount of branches from one “motherbore” in Russia

As seen on the chart (Figure 8), the lion’s share of time spent on tripping operations. Technology

drilling of fishbone well selected according JSC “VankorNeft” requirements to guarantee run liner to the main trunk. However as the international experience of multilateral wells shows, there is no need to drill laterals with a smaller diameter, enough to do sidetrack down to continue drilling “main trunk” and branches always go up. Thereby allowing liner movement on the bottom of the borehole along the main trunk. If there is no transition diameter between the “main trunk” and branches, pretty hard to ensure quick sidetrack by RSS - BHA, PDM – BHA may be used to drilling fishbone by the with the same diameter of main trunk and branches. Nevertheless, it increase the risk of BHA stuck and problems with BHA steerability, which in turn can lead to loss of the trajectory. The next step in the drilling of multilateral wells is to use a high build rate rotary steerable systems (HBR - RSS), which will provide a quick sidetrack with a guarantee to hol trajectory within drilling tunnel. HBR – RSS will significantly reduce the time to build the fishbone well with uncased branches.

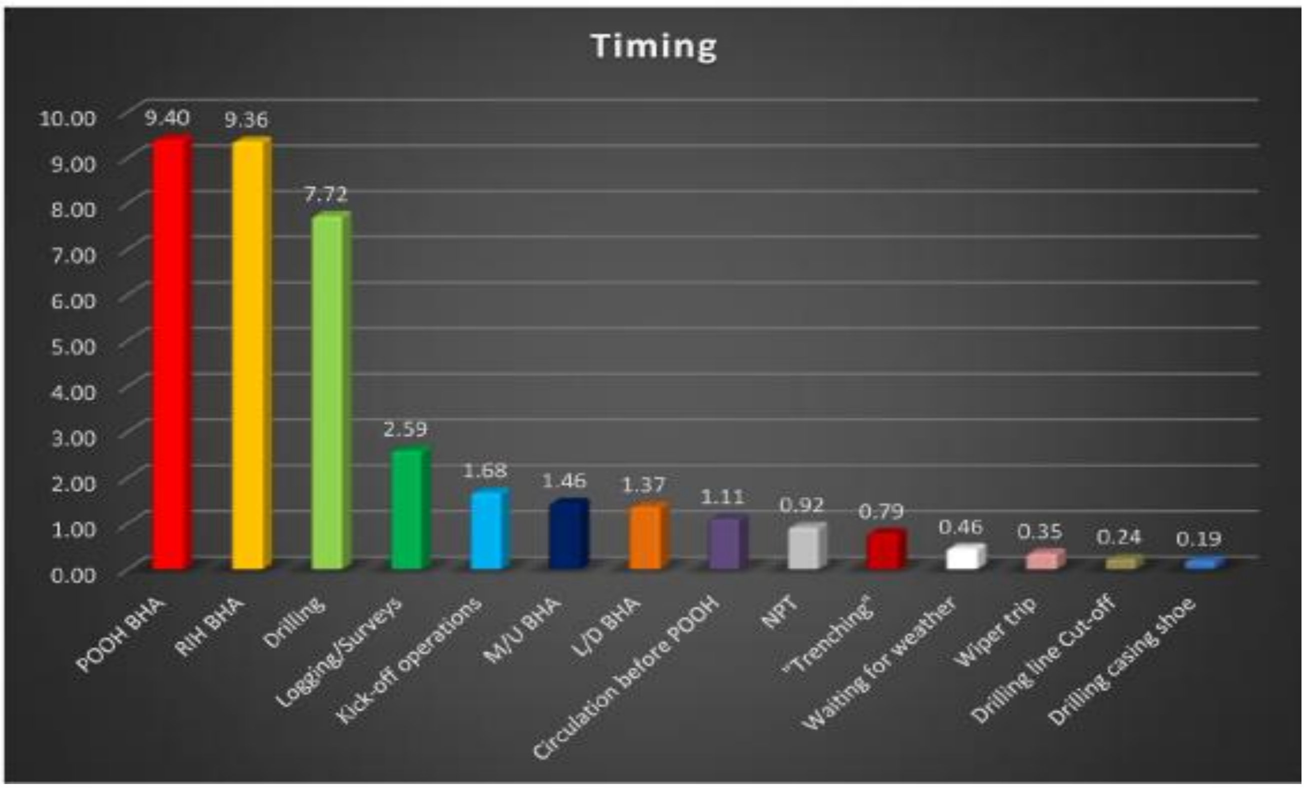


Figure 8—Timing

Considering the logging data while drilling, namely the caliper-image, there are 9 repeating intervals, the average length 5 meters every 100 meters, which recorded the diameter increase (dark fill).Highlighted intervals timed sidetrack intervals from the main trunk, oriented upward in borehole. As seen on (Figure 9), caliper readings allow to control the position of the branches junction relative to the main horizontal wellbore.Geological cross section of the final horizontal section with branches is shown in Figure 10. Color fill,displays radioactivity of rocks, where yellow - sandstone corresponds with varying degrees of clay, gray– argillites, blue – tight rocks. Branches drilled out all effective bed thickness NH1, where some of the branches crossed the top of formation to confirm and clarify the structure within a horizontal section drilled.

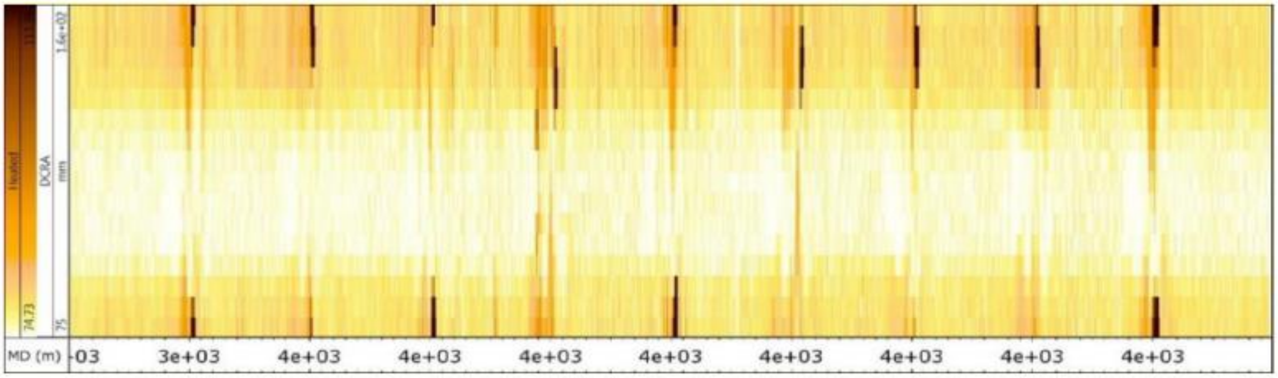


Figure 9—Caliper-image. There are nine repeating intervals, the average length 5 meters every 100 meters, which recorded thediameter increase (dark fill). Highlighted intervals timed sidetrack intervals from the main trunk, oriented upward in borehole.

Geological cross section of the final horizontal section with branches is shown in Figure 12. Color fill,displays radioactivity of rocks, where yellow - sandstone corresponds with varying degrees of clay, gray– argillites, blue – tight rocks. Branches drilled out all effective bed thickness NH1, where some of thebranches crossed the top of formation to confirm and clarify the structure within a horizontal sectiondrilled.

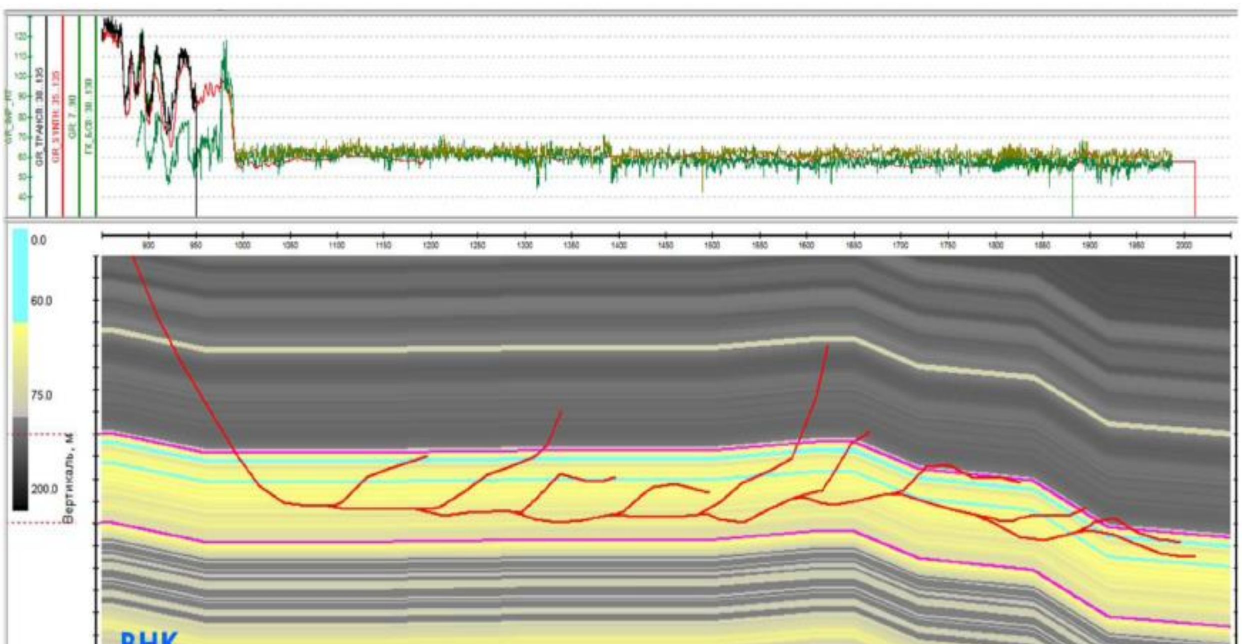


Figure 10—Geological cross section of the final horizontal section with branches. Upper track - displays curves of gamma ray logging,where the green shades presenting curves from different tools while drilling, the black curve - the data from the previous section andred - simulated gamma ray curve. Lower track - geological cross section based on gamma ray data

Conclusion

In the end of December, 2014 the first fishbone well in the Vankor field was drilled and in January it started produce oil. Applied technology allows to produce sidetracks without whipstock or other special technical equipment's. The inclination angle in laterals reached 101 deg.According to production test of first unique multilateral horizontal well at Vankorskoe field initial production rate was twice higher against expected production debits.Due to this type of well was first at oil industry to Vankoroil Company and in general to Rosneft the main issue was to estimate efficiency of this multilateral well. Efficiency estimation was made against earlier traditional horizontal well which was drilled in similar formation properties and reservoir conditions.According to production comparison initial production rate of current multilateral well was twice higher than traditional one. If analyse the data after three month working the values of production rate from multilateral well was four times higher than traditional horizontal well. Significant difference of production rate after three month working could be that the intensity decline of production rate till stable regime working for traditional horizontal well usually in current formation faster than for multilateralwell. It is also assumed that for multilateral well stable regime is not yet reached and gradual productionrate decline will be observed.Monitoring and analysing of working regime for current well has been continuing and experts fromoperatin company has plans to conduct several more similar wells but with more complicated completionsystem.During planning next horizontal wells in formation layer Nch1 with complicated multilateral designswill allow improve production efficiency and involve in the development of additional oil and gasrecovery.Also for further planning to drill similar wells, it is necessary to take into account drawbacks of thechosen method for drilling multilateral well. One of the main drawback is significant part of time spentfor round-trip operations during drilling of the horizontal part. At current well total tripping time operationis approximately 50% of the total construction time of horizontal multilateral section. Significant part ofthe time could be reduce in case of the size of the bit will be the same for all branches and main horizontalhole. Also due to small bitsize of branches in current well only gamma ray curve could be logged. Triplecombo logging data was used only within main borehole. The dimensions of triple combo logging whiledrlling tools was not allowed to use them during drilling branches holes with bit size smaller than mainborehole.If to talk in general, the drilling of horizontal multilateral wells has significant prospects for implementationdirectly for the Vankorskoe field and also in development of Vankor cluster. Implementationof multilateral wells will increase the oil recovery and efficiency development of project as a whole.

Chapter-3

FISHBONE DRILLING SUPERIOR TO FRACTURING

Dreamliner is basically giving engineers an alternative to hydraulic fracturing, where rock is fractured by a pressurised liquid, making cracks in deep-rock formations through which natural gas, petroleum, and brine can flow through.

By using the Dreamliner MST, up to 200 lateral channels are created in the reservoir, each 40ft-long, which allows the operator to increase recovery rate and drain reservoir faster than hydraulic fracturing.

This method comes with challenges, because all targeted intervals have to be consistently stimulated. Also, the growth of hydraulic fractures in the vertical direction can be difficult to predict,you risk entering gas or water bearing formations. Operations can be complex and costly.

Using several smaller channels limits any risk of going too far into the rock. The system also uses less resources; 95% less fluid consumption than normal fracturing. "We can eliminate or greatly reduce the need for chemicals," the researchers say, which would lessen the environmental impact of groundwater contamination and the disposal of recovered stimulation fluid considerably.

Direct environmental impacts from well stimulation include contamination to water supply, induced earthquakes, and impacts on air quality. Using less environmentally damaging chemicals reduces the risk of polluting the surrounding area.

A Dreamliner design network also minimises expensive equipment; the entire operation can be completed without the need to bring a frack truck or a fracking vessel to the drill site. The reduction in man-power and the simplicity of the system means that it is a safer alternative, with a decreased risk of injuries to personnel.

Also MST productivity does not decline over time, which is the case with fractured wells due to fracture closures. The system is much more efficient than drilling conventional laterals and can drain a well more rapidly.

Fishbones has developed a unique and cost-effective technology to get more production out of challenging reservoirs, and with the support from big names it could soon become a global, fully operational service company. The first task was to achieve simplicity, accuracy and efficiency with the Dreamliner, so the hard part is done.

3.1 A Comparison between Multi-Fractured Horizontal and Fishbone Wells for Development of Low-Permeability Fields

Oil and natural gas from unconventional reservoirs such as tight-gas sands is being targeted to contribute a significant share of the world's energy supply in the next two decades. These reservoirs have common characteristics and geographical uniqueness technically and economically. Several obstacles remain in their developments. The challenge is not in discovering the reservoirs, but is the lack of technology and knowledge to obtain high-productivity of wells.Over the last two decades, horizontal well has become a well-established technology for the recovery of oil and gas from low-permeability reservoirs. The major advantages of using horizontal wells are increasing productivities, minimizing gas and water coning, extending areal sweep, and connecting vertical fractures. However, unfractured single-bore horizontal wells still do not deliver economical oil and gas production rates in many low-permeability reservoirs. Therefore, multifractured horizontal wells have been employed, with significant added-cost, in the oil and gas industry. The major problems associated with this type of wells are rapid well productivity decline due to fracture closure and uncertainty of fracture placement due to the lack of knowledge of formation stresses. The recent advances in drilling multilateral wells have opened another alternative for cost-effective development of low permeability oil and gas fields. This paper reports our comparison of using multi-fractured horizontal wells and using fishbone wells, a special category of multilateral wells, for development
of a tight-gas reservoir. The conclusions should be equally valid for tight-oil reservoirs. Giger et al. (1984) presented the first mathematical model for analyzing productivity of horizontal wells intersecting fractures. Giger et al.’s model does not rigorously couple the flow in the reservoir and in the fracture. Karcher et al. (1986) and Soliman et al. (1990) adapted Giger’s model in their numerical simulators for productivity improvement studies.

Raghavan and Joshi (1993) presented a mathematical model for predicting productivities of horizontal wells with multiple transverse fractures. The model uses the effective wellbore radius (in radial flow) to simulate the fluid flow toward the fractured well. Fluid flow within the fractures was not considered. The model presented by Li et al. (1996) considers the reservoir linear flow, fracture linear flow, and fracture radial flow. Guo and Schechter (1997) presented a more rigorous mathematical model coupling the reservoir linear flow and fracture linear flow. But the fracture radial flow near wellbore was not considered. Wan and Aziz (2002) presented a semi-analytical well model for horizontal wells with multiple hydraulics fractures. Wei and Economides' (2005) model couples reservoir linear flow, fracture linear flow and fracture radial flow with choking effect. Guo et al. (2008) published a mathematical model that couples the reservoir radial flow, reservoir linear flow,fracture linear flow, and fracture radial flow including choking effect. This model is considered to be most complete and thus used in our work for predicting productivity of multi-fractured wells.

For multilateral wells, Raghavan and Joshi (1993) also presented a model for predicting productivity of root-type multilateral wells. The model uses the effective wellbore radius (horizontal radial flow) to simulate the fluid flow to the horizontal drain holes. Retnanto and Economides (1996) published a simple formulation of multilateral well productivity for pseudosteady state flow. The formulation was obtained by combining a 1D (linear flow) model and a 2D (radial flow) model in the whole drainage area. Larsen (1996) proposed a mathematical model which is similar to Raghavan and Joshi's (1993) model in the sense that horizontal drain holes are simulated by vertical wellbores located at the midpoint of well elements. Guo et al. (2008) published a more complete model coupling reservoir radial flow, reservoir linear flow, and vertical radial flow. This model is used in our work for predicting productivity of fishbone wells.

3.1.1 BASE OF COMPARISON

This section presents the base of comparison between multi-fractured and fishbone wells in the aspects of engineering and economics analyses. It outlines well models, assumptions, and base data used in the analyses.

Guo et al.'s (2008) well productivity model for multi-fractured horizontal well . The reservoir section includes an outer (non-fractured) region and an inner (fractured) region. It was assumed that a pseudo-steady state radial flowexists in the outer region, reservoir linear flow dominates in the inner region, linear flow exists along the fractures, and radialflow prevails in the fracture near the wellbore. The outer region supplies fluid to the inner region. The inner region transports the collected fluid to the horizontal wellbore. It is believed that the following factors govern the long-term productivity of a multi-fractured horizontal well:

- The efficiency of fluid transport within the drainage boundary (outer region) to the fractured region (inner region),
- The efficiency of fluid transport in the fractured region (inner region) to the fractures,
- The efficiency of fluid transport along the fracture to the near-wellbore region,
- The efficiency of fluid transport in the near-wellbore region to the horizontal wellbore, and
- The efficiency of fluid transport in the fractured region (inner region) directly to the horizontal wellbore.

For the low-permeability reservoirs considered in this study, the effect of the last factor on well productivity is assumed to benegligible. The production rate of a multi-fractured gas well can be expressed as:

$$q = \frac{\bar{p}^2 - p_{wf}^2}{\dfrac{1}{J_{RF}} + \dfrac{1}{J_L} + \dfrac{1}{J_r}}$$

where *q* is gas well production rate, *p* is the average reservoir pressure, *JRF* represents the flow efficiency in the outer region for fractured well, *JL* represents the coupled flow efficiency in the inner region and in the fracture, and *Jr* represents the flow efficiency near the wellbore in the fracture. Definitions of these parameters are referred to Guo et al.'s (2008) work. Fishbone wells fall into a special category of multilateral horizontal wells where all the laterals are placed in the same pay zone. Guo et al.'s (2008) well productivity model for fishbone well. The reservoir section includes an outer (non-drilled) region and an inner (drilled) region. It was assumed that a pseudo-steady state radial flow exists in the outer region and reservoir pseudo-linear flow dominates in the inner region. The outer region provides fluid to the inner region. The inner region transports the fluid to the horizontal wellbore. It is believed that the following two factors govern the long-term productivity of a fishbone well:

- The efficiency of fluid transport within the drainage boundary (outer region) to the drilled region (inner region), and
- The efficiency of fluid transport in the drilled region (inner region) to the horizontal wellbore.

The production rate of a fishbone gas well can be expressed by:

$$q = \frac{\overline{p}^2 - p_{wf}^2}{\frac{1}{J_{Rf}} + \frac{1}{J_{PL}}}$$

Where,

- *JRf*represents the flow efficiency in the outer region for fishbone well
- *JPL* represents the flow efficiency in the inner region (reservoir linear flow and vertical radial flow.

To compare the performance of multi-fractured and fishbone horizontal wells in developing a generic low-permeability gas field, the following assumptions are made:

- The number of fishbone wells is equal to that of multi-fractured wells.
- Locations of fishbone wells are same as that of multi-fractured horizontal wells.
- All the multi-fractured horizontal wells have the same number of equal-length fractures.
- All the fishbone wells have the same number of equal-length rib holes.
- The number of rib holes in a fishbone well is equal to twice the number of fractures in a multi-fractured well.
- The length of rib hole (*L*) in a fishbone well is equal to the fracture half-length (*xf*) in a multi-fractured well.
- All the fractures are evenly distributed with the same fracture spacing.
- All the rib holes are evenly distributed with the same rib hole spacing.
- Rib hole spacing in the fishbone wells is equal to the fracture spacing in the multi-fractured wells.

Material balance and NODAL analysis technique were used in this study to generate production forecast for both multifractured horizontal wells and fishbone wells. Economics analyses were performed based on NPV calculations. Reservoir property data are summarized. Data for tubing performance are listed.

[Guo et al.'s (2005) 4-phase flow model was used for tubing performance calculations.]

Chapter 4

New Method to Estimate IPR for Fishbone Oil Multilateral Wells in Solution Gas Drive Reservoirs

Multilateral wells have been widely applied as production technology to access the difficult geological formations and unconventional reservoirs. Multi-branched horizontal wells have many advantages compared to conventional horizontal wells such as fast depletion and enhanced sweep efficiency especially in water/gas conning area. Moreover, larger drainage area and high single well production rate can be obtained using fishbone wells. Fishbone shaped multilateral wells proved better productivity than multi-fractured horizontal wells in relatively low permeable reservoirs (Guangyu et al. 2012). Generally, multilateral well is defined as a well with multiple branches in the lower bore-hole targeting the pay zone in the same layer or different layers. Multilaterals can be either complex multi-branched wells or simple dual opposing laterals. Depending on the main well-bore the multilateral well be classified simply.

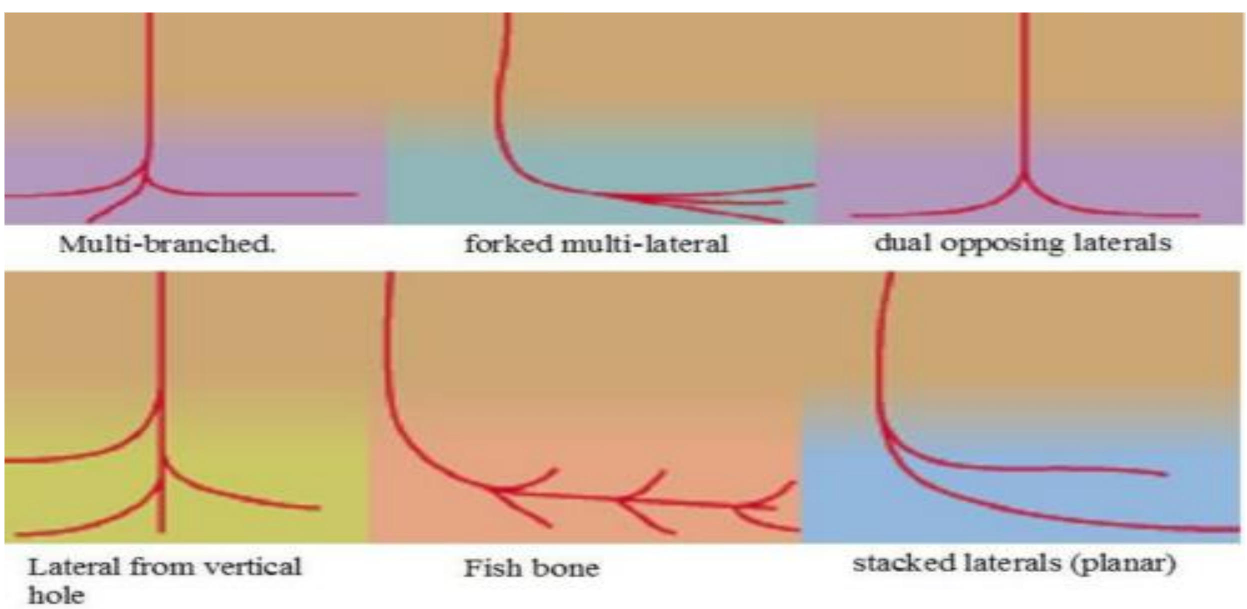


Figure 4—Classification of multilateral wells (modified after Bosworth et al. 1998)

1.Root well: when the main well bore is vertical

. 2. Fishbone: when the laterals drilled out from horizontal wellbore.

Multilateral wells are classified from level 1 to level 6S based on the complexity of the junctions. For instance, level 1 is open hole completed and level 4 has casing and cement in both the main wellbore and junction (Fig. 13).

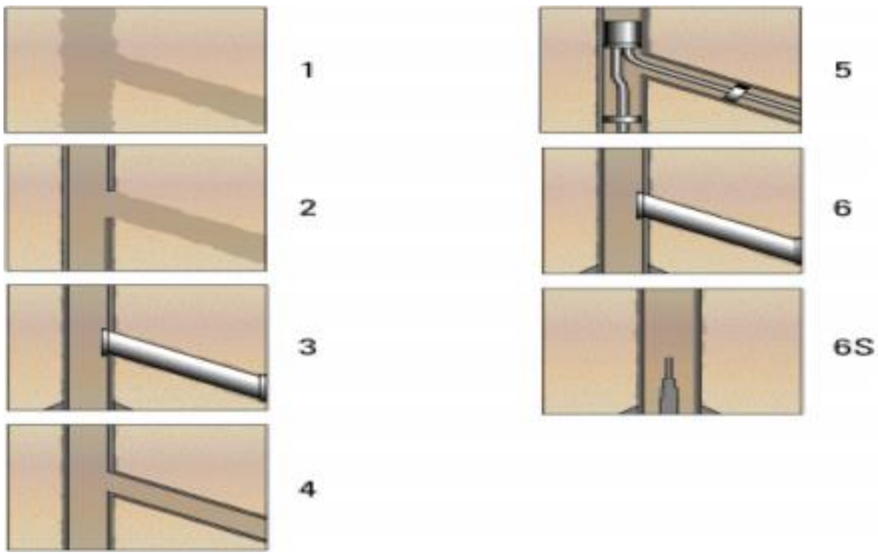


Figure 13—Classification of multilateral wells based on junction complexity (Bosworth et al. 1998)

In this paper we are interested in simple fishbone type without down-hole smart well completion or any down-hole valves in the laterals. The prediction of fishbone well productivity is relatively simple because all the laterals (rib holes) have roughly the same pressure in the main wellbore (backbone hole) (Fig. 14). Prediction of root well productivity is more complicated because the pressures in the laterals can be significantly different and wellbore hydraulics plays important role.

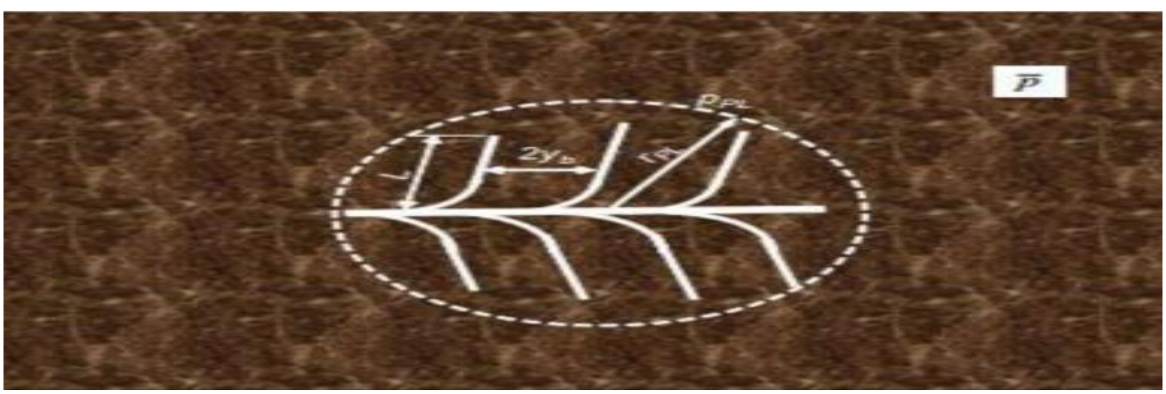


Figure 14—A horizontal fishbone well section (Guo et al. 2008)

4.1 METHODOLGY RESERVOIR

Model Description A simple synthetic, three-phase and three-dimensional model was built based on a reference structure of fish bone wells (Sarfare 2004). A commercial simulator was used to model solution gas drive reservoir. Single fishbone multilateral well was placed in the reservoir with different numbers of rib holes from 2 to 14 radiated from the main horizontal wellbore. The number of cells was 61, 21 and 11 in x, y and z-direction respectively. The well was located in (1, 11) (x, y) as shown in Fig. 4.

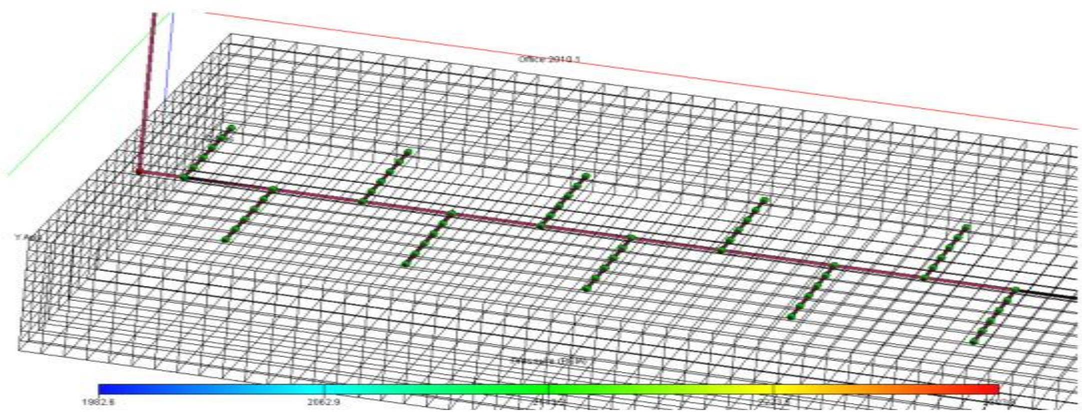


Figure 15—Example of schematic of fishbone structure contains 10 rib hole.

The basic assumptions of this model are:

1. All the horizontal branches are evenly radiated from the horizontal well bore.

2. All the rib holes have the same length (L).

3. The space between the rib holes (2yb) is constant.

A box shaped reservoir was made to simulate the base case with a constant thickness. The homogeneous porous media has a porosity of 0.1 and anisotropic permeability with values of 10, 10 and 1 md in x, y and z, respectively. A multilateral fishbone well was located in the reservoir. A constant initial water saturation of 0.14 was assigned to all cases. The properties of black oil used for the base case are reported in Table 2. The base data used to develop IPR curves were reported in Table 3 and Table 4. The effect of capillary pressure and non-Darcy flow were neglected. Neither damage nor stimulation was present Figure 7—Example of schematic of fishbone structure contains near the rib holes assuming the use of free formation damage Drilling-in fluids or acid wash after the completion.

Table 1—Bottomhole pressures

NO.	Pwf
1	14.7
2	400
3	800
4	1200
5	1600
6	2000
7	2400
8	2800
9	3200
10	3600

Table 2—Fluid properties

P	Rs	Bo	μ_o
psi	mcf/STB	bbl/STB	cp
500	0.054	1.045	1.6667
714.286	0.0558333	1.0474	1.3725
1428.57	0.125625	1.08002	1.1684
2142.86	0.215357	1.124	1.0193
2857.14	0.335	1.18504	0.9059
3571.43	0.5025	1.27335	0.8188
4285.71	0.75375	1.4094	0.7451
4642.86	0.933214	1.50811	0.430698
5000	1.1725	1.64093	0.177561

Table 3—Reservoir data.

Variable	Base case value	Unit
Reservoir X- coordinate	20000	ft
Reservoir Y-coordinate	10000	ft
Reservoir Z-coordinate	750	ft
Permeability in X-direction	10	mD
Permeability in Y-direction	10	mD
Permeability in Z-direction	1	mD
Porosity	10	%
Bubble point pressure	5000	psi
Initial water saturation	14	%
Critical gas saturation	0	%
Residual oil saturation	14	%
Oil density	54.637	lb_m/ft^3
Gas density	0.068432	lb_m/ft^3
Water density	62.4	lb_m/ft^3

Table 4—Fishbone well data.

Variable	Base case value	Unit
$2y_b$	1290	ft
L	2857.14	ft
n	8	-
d	0.3	ft

4.1.1 DIMENSIONLESS IPR CURVES

To generate IPR curves, bottom-hole following pressure should be plotted versus oil flow rate. A small time step was applied at the beginning of each simulation run to model the initial stage of well production. The simulation runs were starting from initial reservoir pressure less than the bubble point pressure and using different values of bottom hole flowing pressure for each run. After that, dimensionless IPR curves were generated by dividing the bottom-hole pressure of each case by the average reservoir pressure and the oil production rate by absolute open flow (AOF). IPR curves were generated in dimensionless form to compare the rate of shifting of each curve when changing some factors. The simulation model was run in two different styles. Firstly, a constant bottom-hole flowing pressure was specified. Secondly, the well was constrained by a constant oil production rate. Constant bottom-hole pressure constraint runs gave better IPR curves than constant flow rate ones. As a result of that, constant bottom-hole pressure constraint was used for all runs. The performance of each case was simulated using 10 different values of bottom-hole flowing pressure as shown in Table 1

4.2 SENSITIVITY ANALYSES OF IPR CURVES FOR FISHBONE WELLS

Fig 8 and 9 show schematic structure of fishbone wells with different rib holes lengths and different distances between the branches. Fig. 10 to 17 illustrate the influence of several variables on IPR curves. The effect of porosity, initial water saturation, API gravity, bubble point pressure, permeability, number of rib holes and their length was investigated. Moreover, the effect of the distance between lateral also was studied. It can be clearly seen that most of these factors have negligible impact on IPR curves. The number of node segments in the simulation model was assumed to be constant during the investigation of the effect of the length of the rib holes. A significant change on IPR curves was addressed by changing number of rib holes.

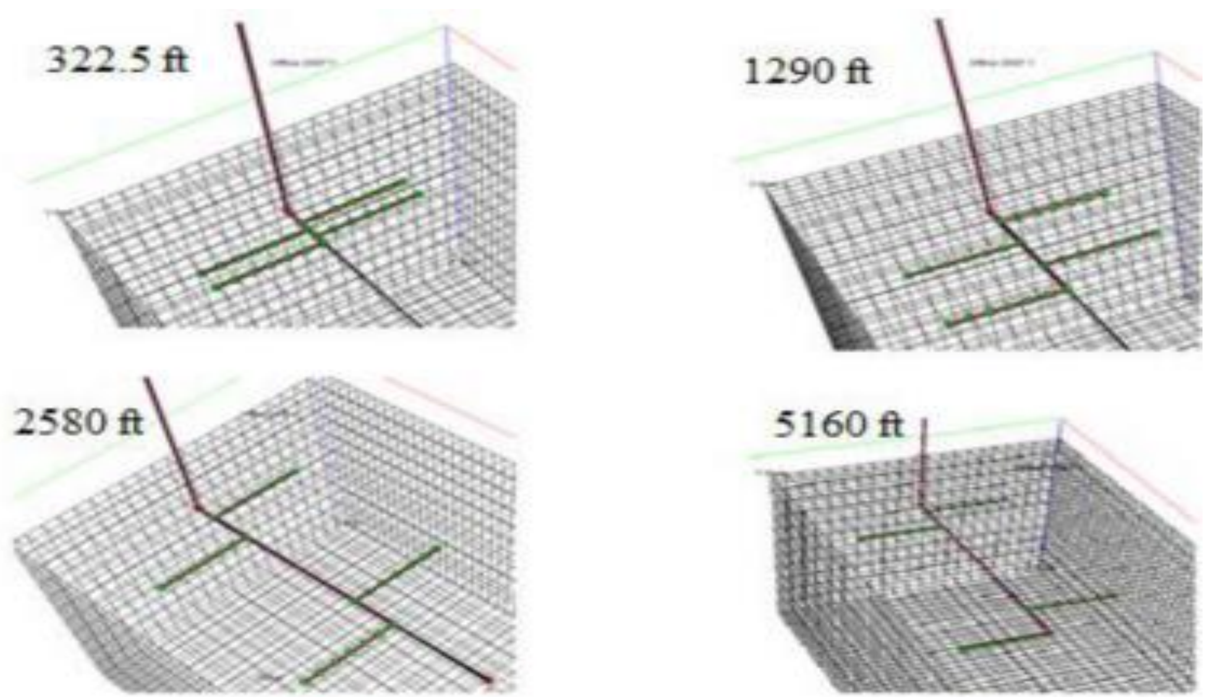


Figure 16—Schematic structure of fishbone wells with different distances between the rib holes

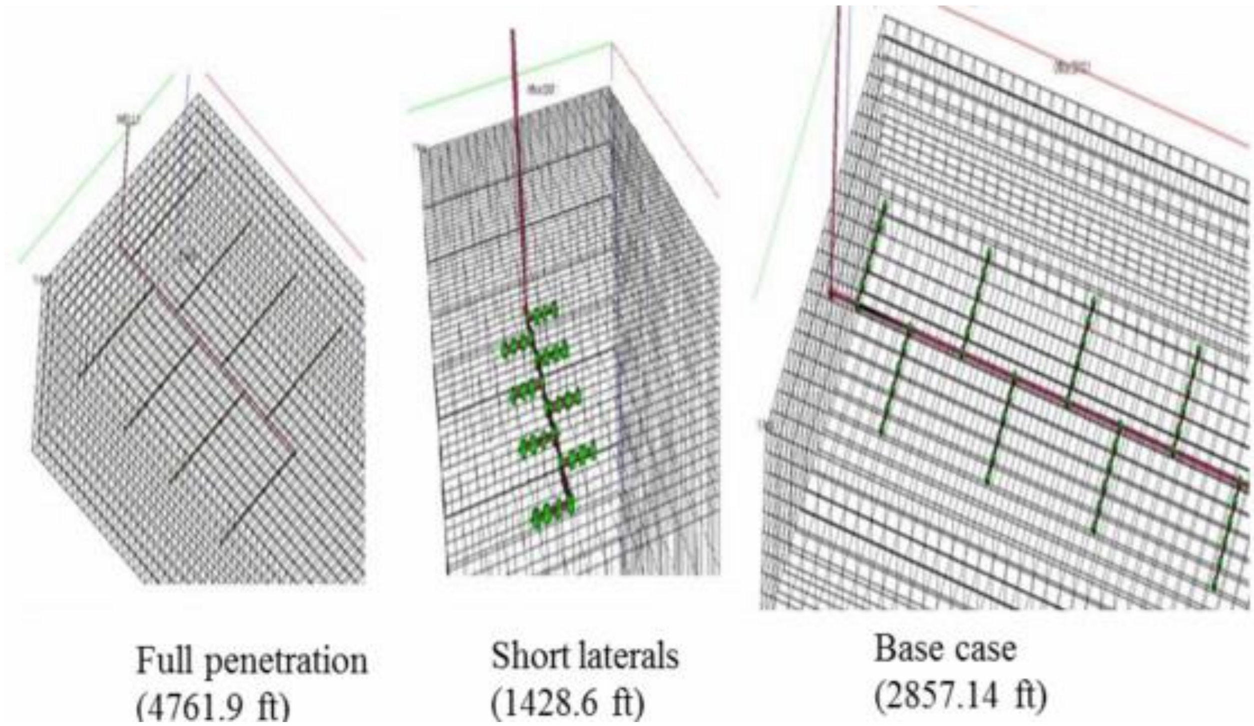


Figure 17—Schematic structure of fishbone wells with different rib holes lengths

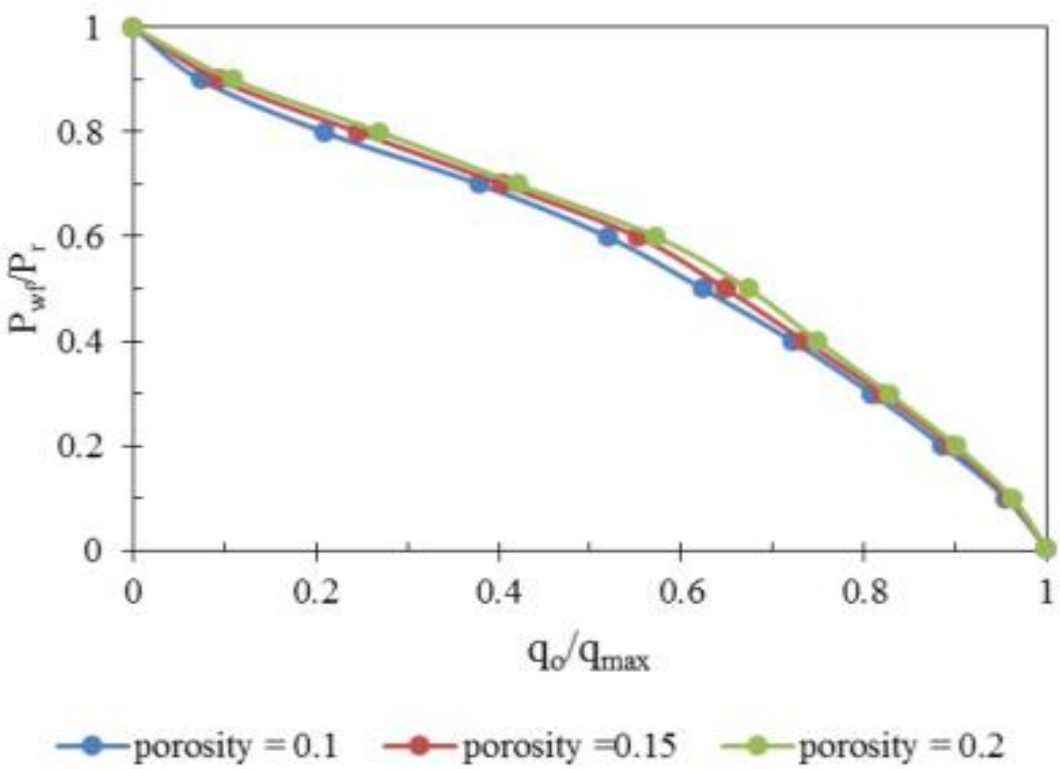


Figure 18—Effect of porosity on IPR curve.

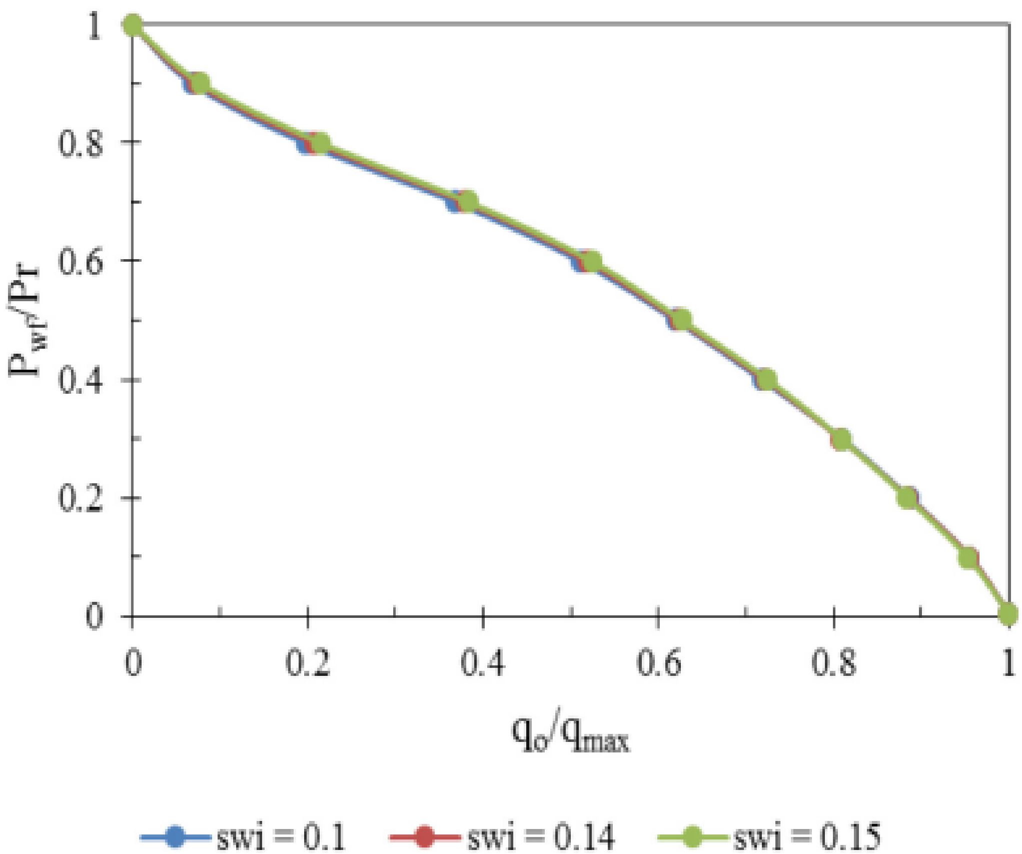


Figure 19—Effect of initial water saturation on IPR curve

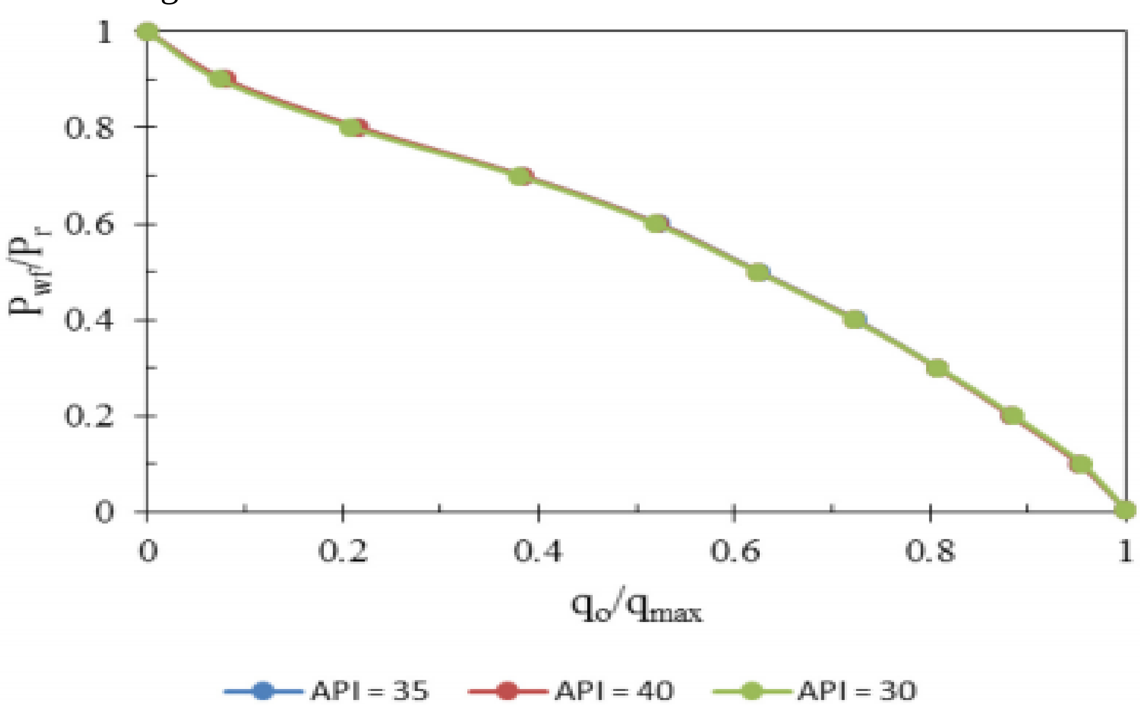


Figure20.Effect of API curve on IPR curve

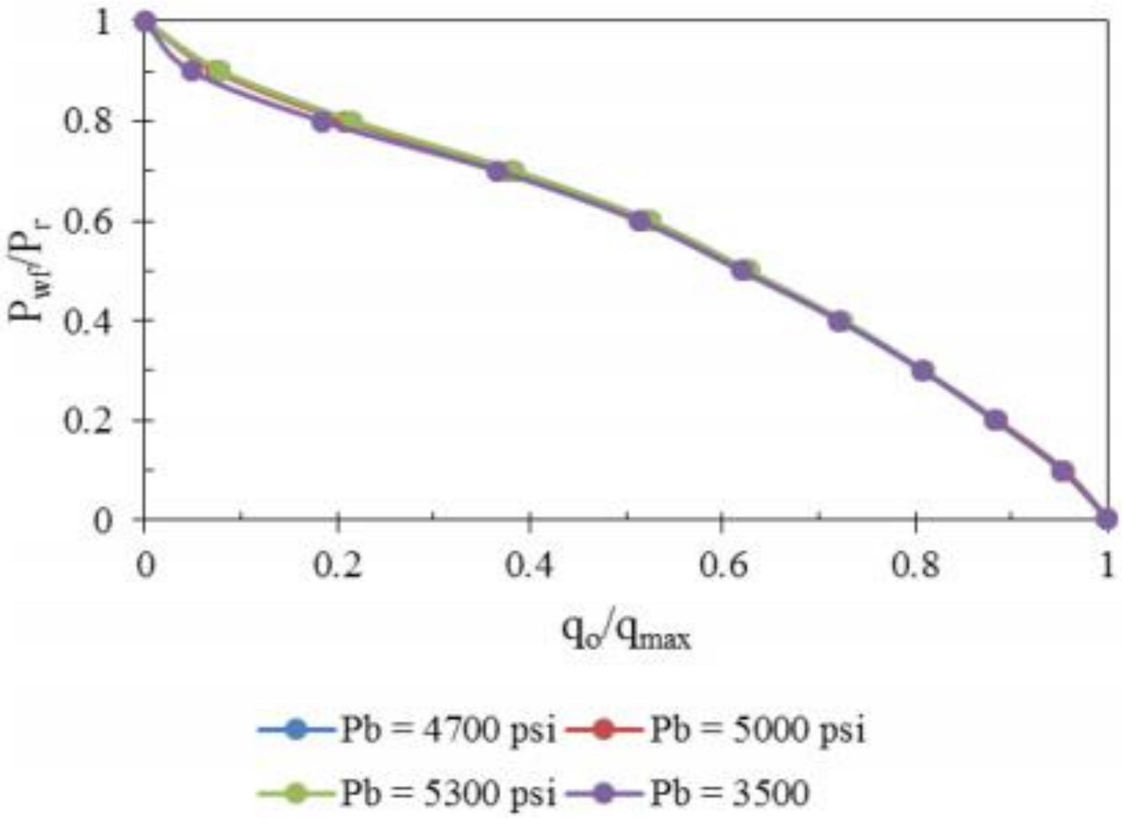


Figure 21—Effect of bubble point pressure on IPR curve.

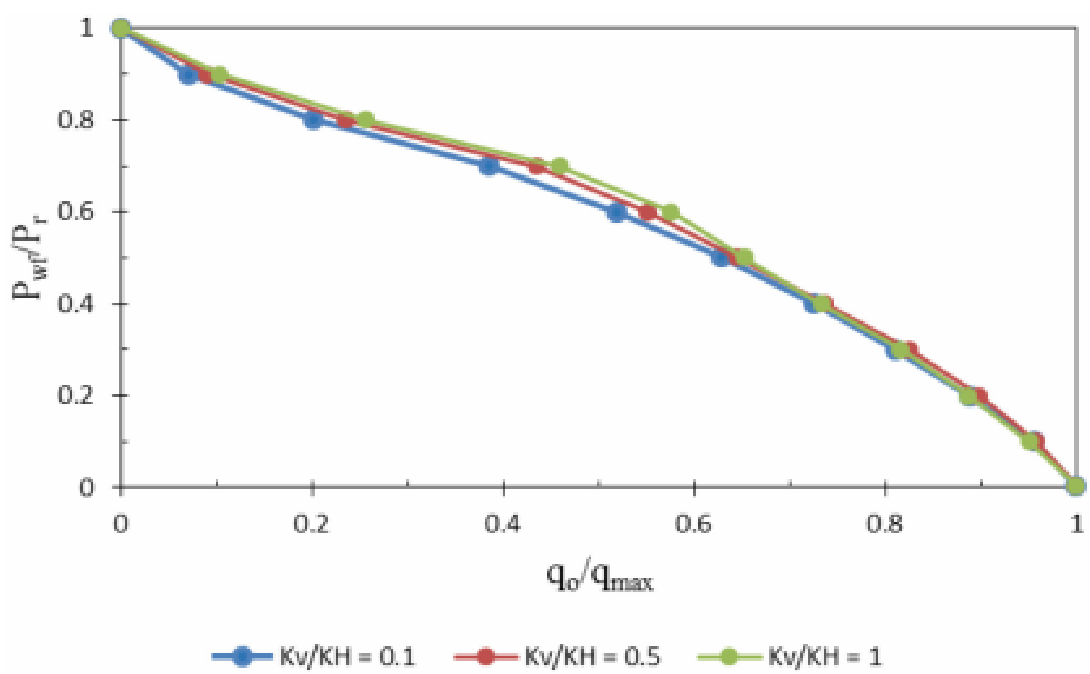


Figure 22—Effect of permeability ratio on IPR curve.

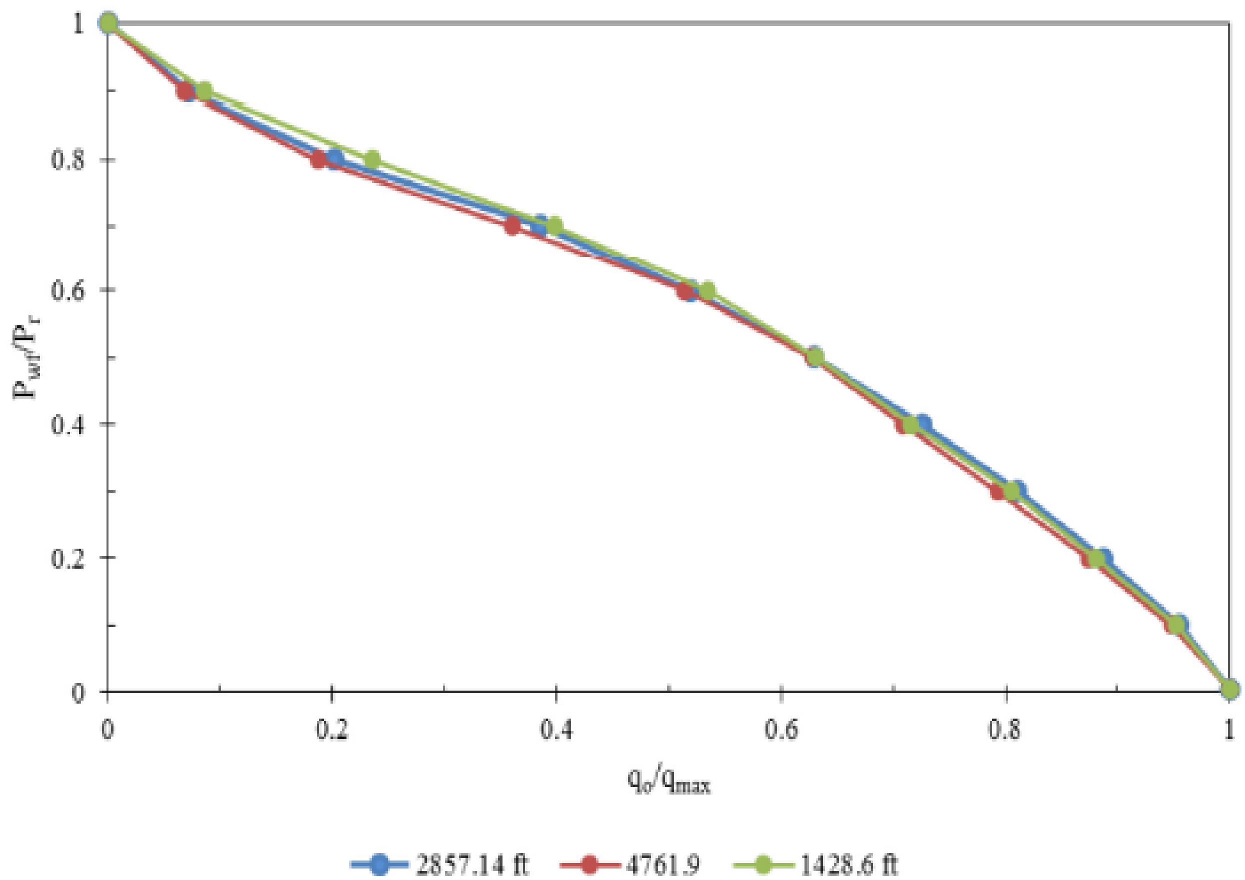


Figure 23—Effect of rib holes length on IPR curve.

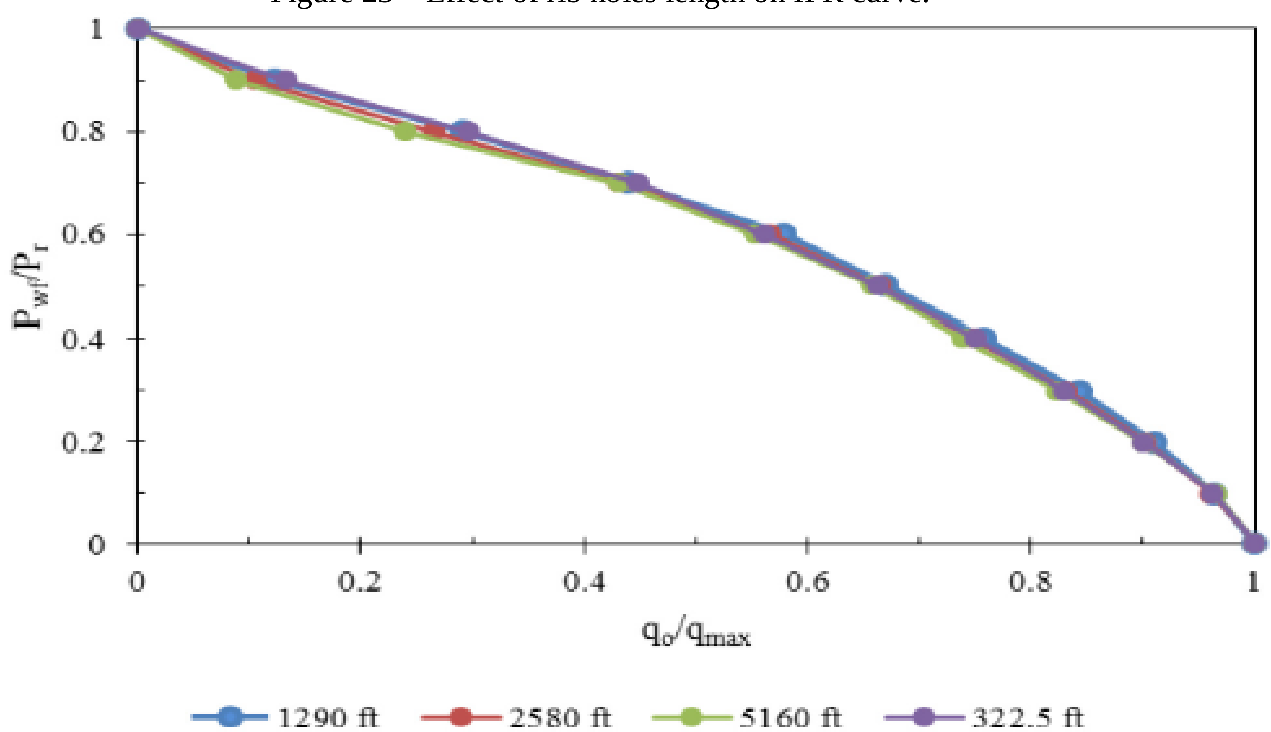


Figure 24—Effect of distance between rib holes on IPR curve.

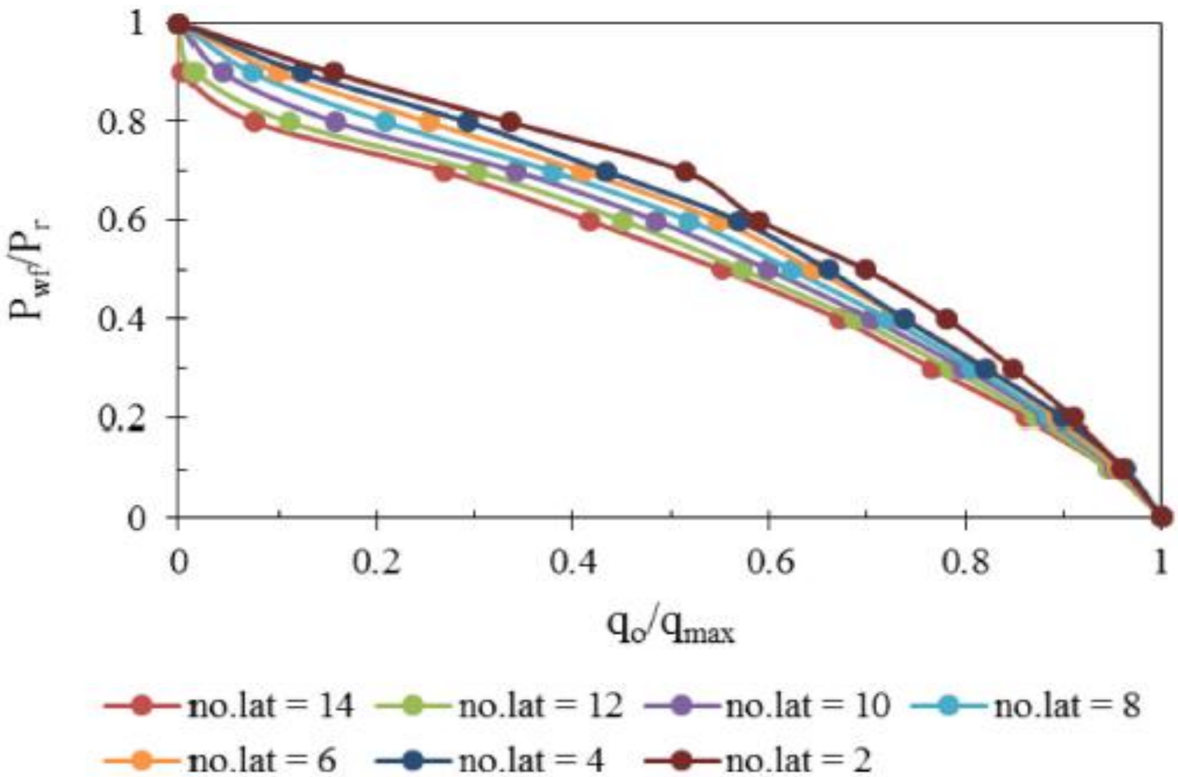


Figure 25—Effect of number of rib holes on IPR curve.

4.3 FISHBONE IPR MODEL GENERATION

Based on the sensitivity analysis, a regression technique was applied of all simulated scenarios toimplement the number of rib holes in the Vogel form equation and the following model was generated:

$$\frac{q_o}{q_{o\,max}} = 1 - (0.0446 * n + 0.1488)\left(\frac{P_{wf}}{P_r}\right) - (0.8288 - 0.0358 * n)\left(\frac{P_{wf}}{P_r}\right)^2$$

Where (n) represents the number of rib holes radiated from the horizontal well bore.

The new model (ABDULAZEEM & AL-NUAIM) was compared with generalized Vogel model whichis generally used when the reservoir pressure is less than the bubble point pressure using data from theliterature (Table 5). Geo’s model (2008) was used to calculate the productivity index. Fig. 18 clearlyshows that the new model matched Vogel’s model when the number of rib holes was small. However, thetwo models separated when the number of rib holes increased. The model can be further correlated to real IPR of existing drilled fishbone multilateral wells. Unfortunately, no real case was found in the literature.

Table 5—Case study using data of fishbone well.

Quantity	Value	Unit
Rib hole spacing ($2y_b$)	1000	ft
Rib hole length (L)	1000	ft
Average rib hole skin factor (s)	5	-
Oil bubble point pressure (P_b)	5000	psi
Effective horizontal permeability (kH)	10	md
Pay zone thickness (h)	50	ft
Average reservoir pressure (p-bar)	4000	psi
Oil formation volume factor (B_o)	1.2	rb/stb
Well drainage area (A)	320	acres
Rib hole radius (r_w)	0.328	ft
Vertical permeability (kV)	2	mD
Well vertical depth (H)	8000	ft
Tubing inner diameter (d)	4	in.
Oil gravity (API)	30	API
Oil viscosity (μ_o)	1.5	cp
Producing GLR (GLR)	500	scf/bbl
Gas specific gravity (g_g)	0.7	air = 1
Flowing tubing head pressure (P_{hf})	800	psi
Flowing tubing head temperature (t_{hf})	150	°F
Flowing temperature at tubing shoe (t_{wf})	180	°F
Water cut (WC)	10	%
Oil-gas interfacial tension (s)	30	dynes/cm
Specific gravity of water (g_w)	1.05	
Number of rib holes (n)	7	
Drainage area shape factor (C_A) based on aspect ratio	5.38	

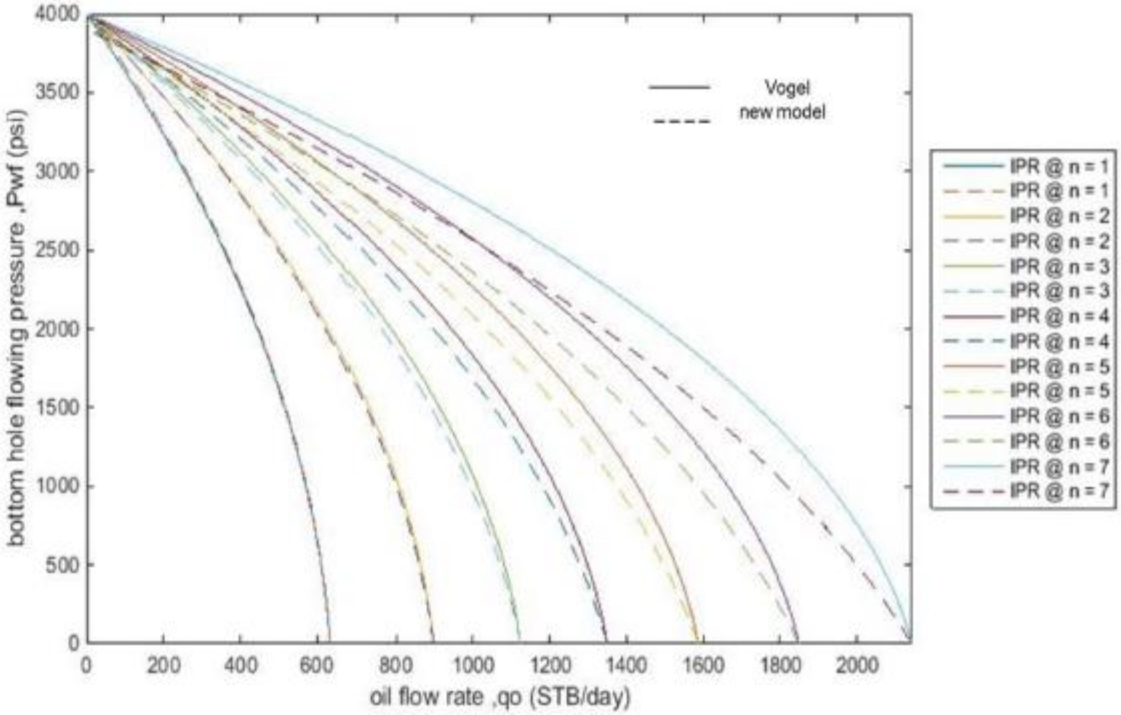


Figure 26—Comparing the new model with Vogel's model.

4.4 CONSIDERATIONS WHEN USING FISHBONE MULTILATERAL WELL

The intensive simulation scenarios showed that there is an optimum number of rib holes indicating thatthe increase in well productivity is not linear with number of radiated laterals. Moreover, the distance andthe length of the laterals should be optimized to avoid increasing the well cost. In contrast to conventionalwells, fishbone wells have higher reservoir contact area resulting into higher production rate. During thesimulation runs, the effect of distance between rib-holes was investigated to understand the interferencebetween the branches. Figure 16 shows the IPR for different distances between the branches ranging from322 ft to more than 1290 ft. The figure shows that interference is an issue at higher rates regardless of thedistances between the rib holes. At low rates, you can see the separation of the IPR indicating minimuminterference at all distances. Verga et al. (2005) studied the effect of interference on the productivity offishbone multilateral wells and found that interference phenomena decreases the efficiency of fishbonewell.

Chapter 5

Fishbone Well Drilling and Completion Technology in Ultra-thin Reservoir

With the further process of oil exploration and development in Puyang layers of Daqing Peripheral Oilfields, a series of problems shall be encountered, such as low recovery rate and high drilling cost. It's hard to solve above problems by only increasing the length of horizontal interval. Fish-bone shaped well, with multilateral wellbores and increased reservoir drainage area, is an effective way to improve the single well production rate.

The advantages of horizontal fish-bone shaped well are as follows:

- Larger drainage area and high single well production rate can be obtained, compared with conventional horizontal well.
- The layers can be effectively connected to reduce the economic risk in heterogeneity stratum, which improved development benefits in low permeability reservoir.
- The single well engineering cost can be reduced, such as drilling operation, land, rig transportation, rig up, rig down, casing, cementing, drilling fluid, waste mud and cuttings dispose, etc..Further more, the cost of surface oil production and transportation are decreased.

5.1 THE OPTIMIZATION PROCESS OF FISH-BONE SHAPED WELL IN ULTRA-THIN OIL LAYER

Though casing program and well path of main hole are similar with conventional horizontal wells, the planning of fish-bone shaped well is more complex. The main design difficulties concentrated on the optimization of the branch number, branch length, branch angle, the offset from the main hole, and the distance among branches.

5.1.1 THE OPTIMIZATION OF BRANCH NUMBER AND BRANCH DIRECTION

Branch number is a major factor for the shape and production of fishbone wells. Combined with reservoir characteristics analysis, reservoir numerical simulation technology is applied to calculate production of fish-bone shaped well with 1 to 6 branches respectively. Fig. 1 shows the relation between the initial daily production and branch number. Numerical Simulation Calculation results show that daily production improves with the branch number increasing, but when branch number is more than four, the initial production would increase very little

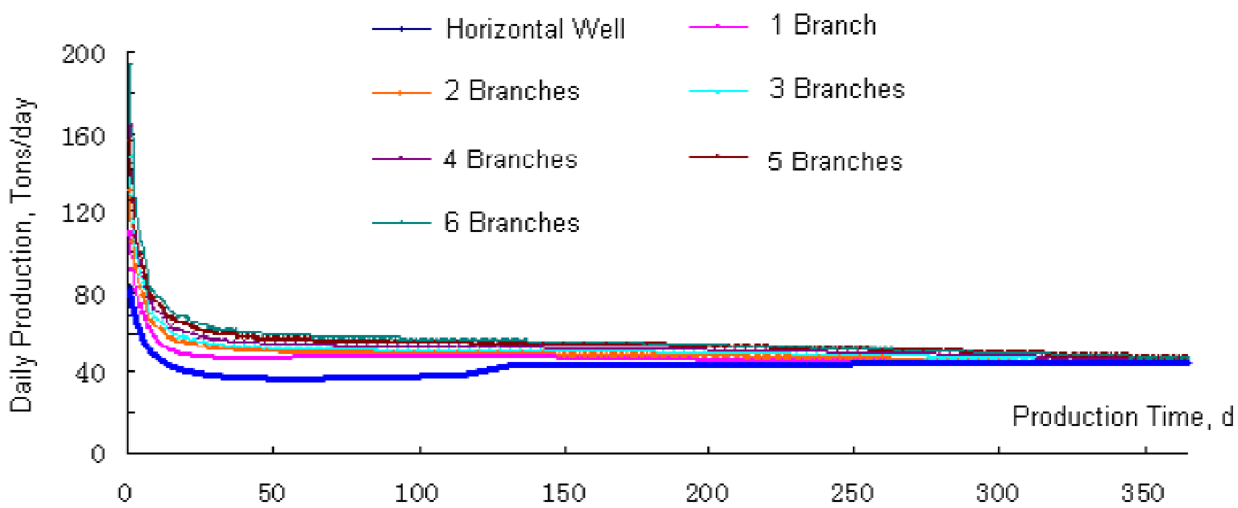


Fig.1 The initial daily production curve in different branch number.

In the condition of same total drilling footage, increasing the branch number means increasing drilling cost. In order to analyze the effect of branch number on production of fish-bone shaped well, four fish-bone shaped wells were designed with same total wellbore length, but different branch number (see figure 2). The calculation results are shown in figure 3.

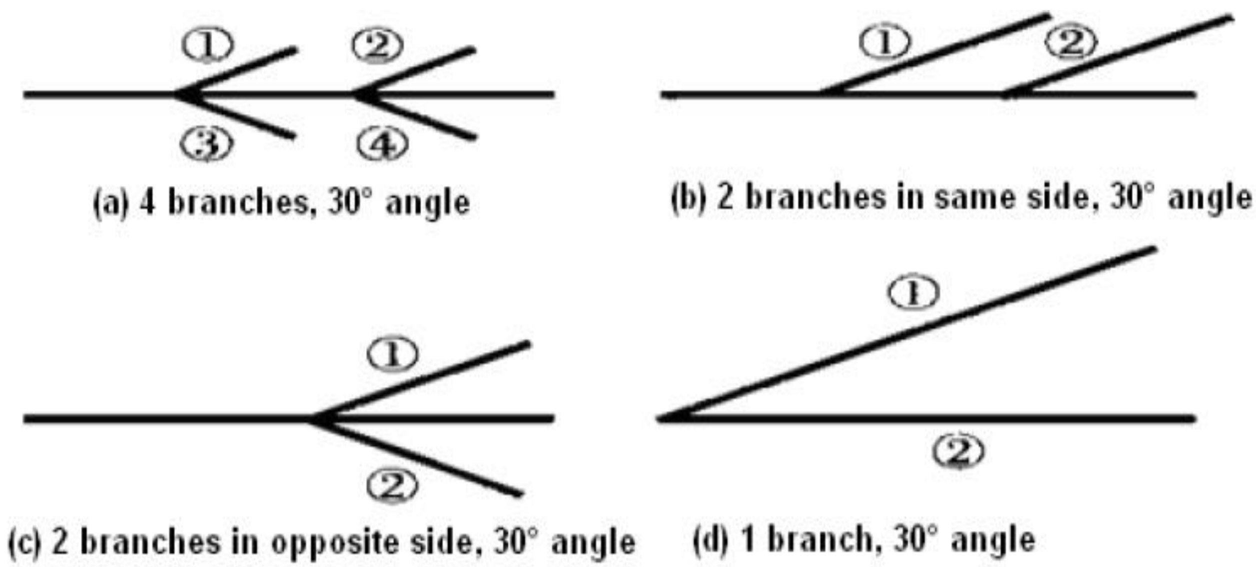


Fig. 2 Fish-bone shaped well models with same total wellbore length, different branch number and angle

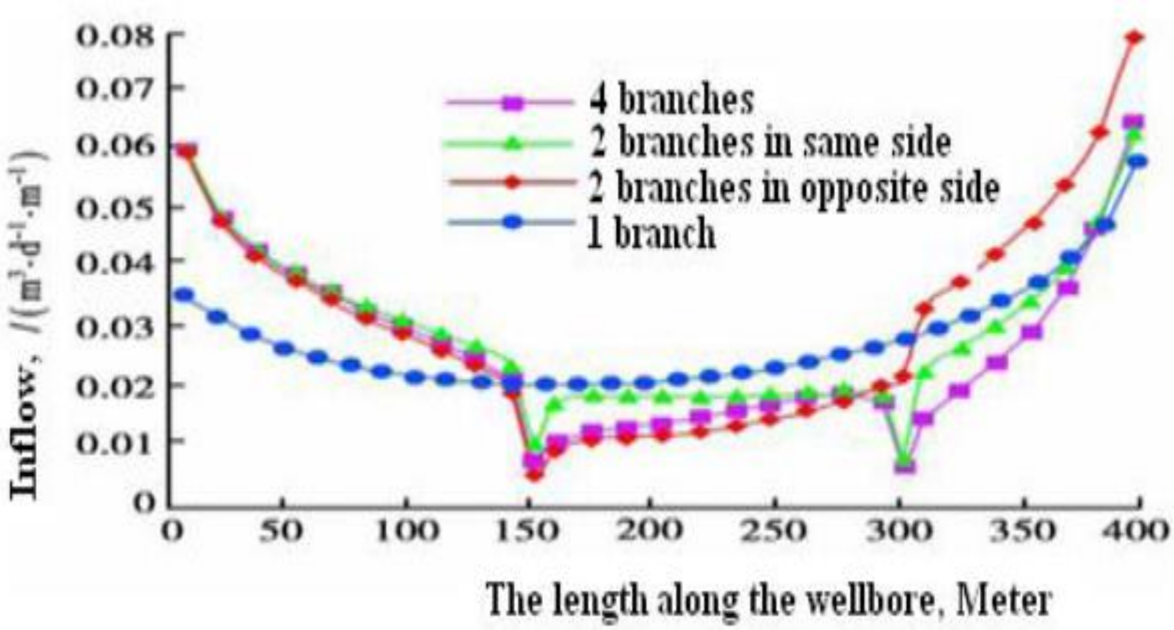


Fig.3 Inflow in main hole with different branch number

The calculation results show that the fish-bone shaped well with branches in opposite side can get more production than that with branches in same side. It is cost-effective to drill four branches fish-bone shaped well in opposite side.

5.1.2 BRANCH ANGLE OPTIMIZATION

With the increasing of branch angle, the control area of fish-bone shaped well is larger. In addition, the increasing branch angle also changes the interference between branch hole and the main hole, and the interference among different branch holes. By means of the prediction model, the production of a four-branch fish-bone shaped well with different angles and a conventional horizontal well are calculated. The comparison results are showed Figure 4.

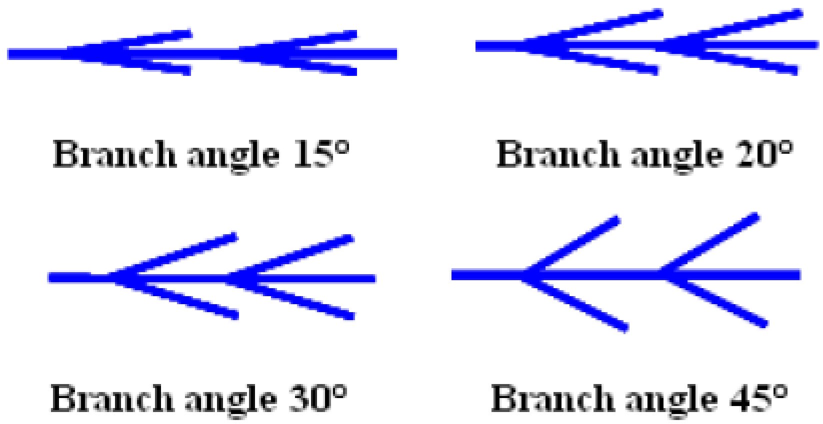


Fig.4 Branch hole planning model with different branch angle.

Table 1 Calculated production with different branch angle

Branch angle (°)	Main hole		branch 1		branch 2		branch 3		branch 4		Total production (m^3/d)
	production (m^3/d)	percentage (%)	production (m^3/d)	percentage (%)	production (m^3/d)	percentage (%)	production (m^3/d)	percentage (%)	production (m^3/d)	percentage (%)	
15	33.2	52.1	6.6	10.4	8.8	13.8	6.4	10.0	8.7	13.6	63.7
20	33.4	51.2	7.0	10.7	8.8	13.5	7.0	10.7	9.0	13.8	65.2
30	33.5	50.7	7.4	11.2	8.8	13.3	7.4	11.2	9.0	13.6	66.1
45	33.5	50.6	7.9	11.9	8.6	13.1	7.5	11.3	8.7	13.1	66.2

The results show that there is little increase in production when branch angle is more than 30°. In considering the maximum capacity, combining with drilling process requirements, appropriate branch angle is from 20° to 30°.

5.1.3 BRANCH LENGTH

Reservoir numerical simulation technology is used to optimize the branch length, which calculated the change of initial production of fish-bone shaped well fishbone as a function of time in branch length of 100 meters, 150 meters, 200 meters and 300 meters. Numerical simulation results show that, with the increase of the branch length, the controlled reserves and initial daily production improve. In order to ensure the safety operation of fish-bone shaped well, the optimal branch length should be 200 meters.

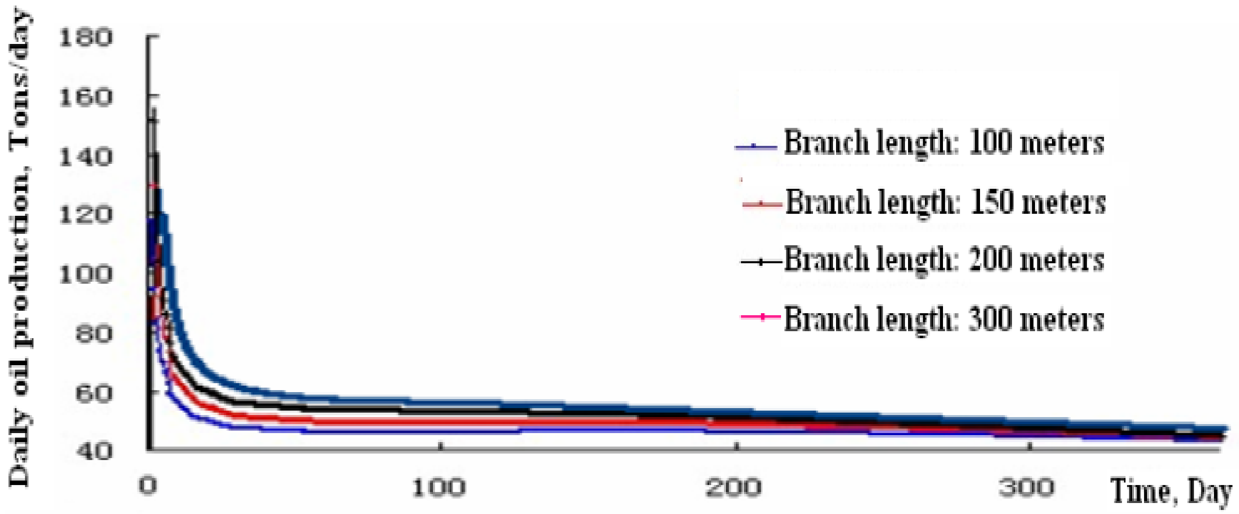


Fig.5 The daily oil production comparison of different branch length

5.1.4 THE DISTANCE BETWEEN BRANCHES

Many factors should be fully considered in selecting sidetrack point, including longitudinal distribution situation of oil and water layer, curvature radius in build-up interval, the relationship between each branch, sidetrack direction, etc.. According to the geological requirement of new wellbore, there must be enough offset between two branches to ensure safety operation, short drilling cycle, cost-effective drilling, oil and gas production improvement. It is relatively appropriate that the span between two branch holes is with 80 ~ 150 meters.

5.1.5 SPECIAL DESING REQUIREMENTS

Due to thin target reservoir, wellbore path should be designed to drill from reservoir high point to low point, extend the direction of oil layer. The sidetrack point of each branch hole should be decided by reservoir coverage rate of main hole.

In addition, the operation sequence is optimized from top to bottom, which means:

- First, drill main hole.
- Second, drill the first branch.
- Third, back to the first sidetrack point, continue to drill main hole.
- Fourth, drill the second branch.
- Fifth, back to the second sidetrack point, continue to drill main hole.
- Sixth, drill the third branch.
- Finally, complete the main hole.

The operation process has the following advantages:

- Judge the development of reservoir according to information while drilling, and choose the best development section to sidetrack.
- Avoid branch hole departing from oil layer.
- Keep the main hole smooth and clean, especially sidetrack points region, which can be helpful for running in completion string safely.

Operation technology of fish-bone shaped well in Ultra-thin oil layer

In the drilling operation of fish-bone shaped well, single bend motor combined with LWD is used to control the well trajectory, which has the following problems compared with conventional horizontal well:

- The thickness of target layer is only 1.5 - 2 meters, and the LWD survey gap is 9 meters, which require that the welllbore trajectory should move along the reservoir development direction to realize maximum sandstone coverage rate.

- Previous operation must provide good conditions for following operation and the running of completion string. Especially in process of openhole sidetrack, fast separation between the main hole and branch hole should be realized, at the same time, the effective sandstone coverage rate should also be considered to avoid significant changes of TVD.

- Shale and sandstone are interbedded in low permeability layer, in which the average shale content is more than 15%. Poor consolidation and poor stability make it difficult to form stable “interlayer wall” between main hole and branch hole in sidetrack point.

- Bad reservoir development, such as featheredging, which results in searching oil upwards and downwards in horizontal interval, increasing the sliding drilling rate and leading to bigger operation difficulty.

- The screen pipe completion in main hole and open hole completion in branches. Because there is no mechanical pilot tool in the separation point between main hole and branch hole, the completion string is easily run in branch hole.

A：OPENHOLE SIDETRACK TECHNOLOGY

Openhole sidetrack technology is a key process to realize safety separation of main hole and branches. If drill branch one by one after finishing main hole, the sidetrack process shall be more difficult because of no support force for motor in sidetrack point. So drilling operation is designed “from high point to low point” which is described in above section. The key technology points are:

- Choose reasonable sidetrack point: ahead of branch hole 6 to 10 meters.
- Adjust tool face opposite to the branch hole direction, and slide drilling 6-8 meters.
- Lift the drill string, pump off, and lower drill string to apply proper WOB. The process is used to test the loading capacity of new wellbore, and judge sidetrack successful or not.

B: INTERLAYER WALL FORMING TECHNOLOGY IN UNCONSOLIDATED FORMATION

For the low permeability reservoir with unconsolidated and loose sandstone and shale interbedded formation. The traditional process in conventional horizontal well, " build inclination first, adjust the azimuth later", has been replaced to use the process of " build inclination and adjust the azimuth at the same time "， which adjusts direction while building. This makes simple separation in one vertical profile transfer to vertical separation in a 3-D profile, which guarantees quick separation between main hole and branch, and form thick and stable “interlayer wall” in unconsolidated formation. At the same time, the decrease of the TVD increment also ensures the effective sandstone coverage rate. The key technology points are:

- Adjust toolface, incline upwards to drill with small WOB, reaming, and make the branch hole raise 1 ~ 2 meters in vertical direction separate 2 ~ 4 meters in horizontal.

- After the stable “interlayer wall” was formed, drill along the designed branch hole well trajectory.
- After the branch hole drilled out, shot trip with reverse reaming, run into the bottom of the branch, and displace reservoir protection fluid.

C: SAFE RUNNING TECHNOLOGY OF DRILL AND COMPLETION STRING

In the process of wellbore trajectory control in each branch hole, the vertical trajectory of main hole should keep below every branch to ensure later drill and completion strings be run in the force of gravity, and along the main hole direction, not enter into the branch hole.
After drilled out, more wiper trip should be executed to make the main hole smooth and avoid the drilling tools entered into the branch hole.

FIELD APPLICATIONS

So far, two fish-bone shaped wells have been drilled, which realize four branch holes in 1.5 meters ultra-thin layers. The Max. vertical distance between main hole and branch hole can reach 117.79 meters, the Max. angle between branch hole and main hole is 31.05 °, single branch footage is 260 meters, and total horizontal length is 1428 meters.

The initial production of this two fish-bone shaped wells is 10 times as much as that of offset wells, and stable output is of 3.5 times, which get good results.

Chapter 6

DIFFERENCE WITH RADIAL JETTING DRILLING

Radial jet drilling was invented in the1980’s and has been used on thousands of wells worldwide since then .It is a low-cost method to drill numerous, small-diameter horizontal laterals from an existing wellbore. When incorporated into a horizontal well, the resulting architecture is sometimes called a “fish bones”.

Recently, the oil and gas industry has witnessed a steady increase in the use of short-radius horizontal drilling operations to enhance well productivity. The trend is expected to continue in the future as oil and gas industries become increasingly aware of the benefits associated with it while targeting thin reservoirs and oil reserves, which are pocketed and scattered. Horizontal drilling and new completion techniques have helped increase production in fields that may be uneconomic with traditional completions. However, these traditional techniques are still expensive and may not be suitable in marginal oil/gas reservoirs. Developing small and marginal fields with traditional techniques is expensive and economically unviable. For example,the cost can range from 1.0 to 10.0 million US$ to drill and complete one well. In addition, with increase in oil usage and demand, the need for finding new reserves has very high importance. Only new discoveries cannot compensate the rate of exhaustion of resources. As 60% of world's production is from matured fields, a better strategy to extend the production life of existing assets is crucial.Therefore new techniques, Radial Jet Drilling, RJD for example can be quite helpful in improving recovery,especially from marginal fields where the hydrocarbons reserves may not justify the high cost of horizontal drilling and hydraulic fracturing.Abrasive water jet cutting of material involves the effect of a high-pressure velocity jet of water withinduced abrasive particle. It is a recent non-traditional machining process, and it is widely used in many industrial applications such as mining, shipbuilding, automotive, etc. (Brooks and Summers 1969).The concept of water jet was first introduced in the 1960s and the initial applications were limited to cleaning and unblocking drains. With the development of new technology and availability of high-pressure pumps, water jetting gained importance and was used on commercial scale to cut soft materials such as cardboard and rubber. Many efforts were made in late 1960s to use water jetting in petroleum industry to drill sub-surface reservoir rocks, but favorable results could not be achieved because of deficient abrasive injection techniques (Birtu and Avramescu 2012). Drilling fluids pumped under ultra-high pressures can enhance drilling performance while maintaining conventional rig operating procedures and safety. The impact of the high velocity fluid stream can significantly assist the mechanical action of the rock bit allowing penetration rates of 2 to 5 times overconventional systems in comparable drilling conditions (Pervez et al. 2011).In 1993, Dickinson et al reamed a large casing and pushed 1¼-inch CT between 25 to 150 ft. into formation for production enhancement (2 – 10 folds). Currently, RJD has been proven to enhance production rates, to reduce decline rates, to reduce near wellbore damage, and to recover more resources from stripper wells (Dickinson and Dickinson 1985; Dickinson et al. 1990; Dickinson et al. 1993; Abdel-Ghany et al.2011).Radial Jet Enhancement has made it feasible to enhance production from more than 1.7 million wells that would otherwise be cost prohibitive to recover. This represents a total potential untapped market of more than $50 billion. Using RJD technology, horizontal channels up to 300 feet can be drilled out from an existing wellbore in any direction, with 1 – 2 in. diameter using high-pressure fluid. In North and South America, RJD technology is oriented toward existing oil and gas wells at depths of 4,500 feet and shallower for productivity improvement.

6.1 WHAT IS RJD?

Abrasive water jet cutting is one of the non-traditional cutting processes capable of cutting wide range of hard-to-soft materials. Radial Jet Drilling is a process of drilling radials of small bending diameter horizontal perforations using water jets at very high pressure in different directions. The diameter of these radials is approximately 1 - 2 inches and lengths up to 300 ft. These radials can be drilled in multiple layers through a same well.

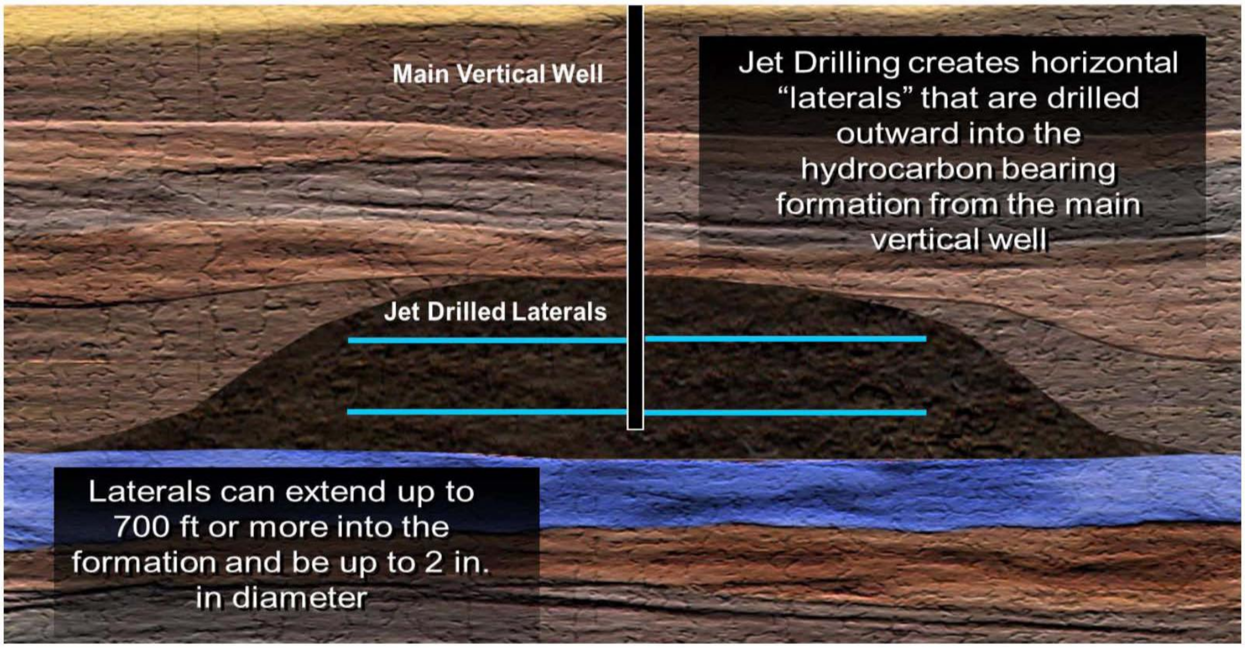


Figure 1—Radial jet drilling (Courtesy of Buckman Jet Drilling)

6.2 RJD PROCESS

Radial jet drilling is a cost-effective alternative way to drill small-size laterals using a coiled tubing unit.It eliminates the need to the conventional bit and mud system. In RJD, high-pressurized fluid is circulated through forward and backward nozzles connected to a high-pressure hose. The energized fluid leaving the forward nozzles is used to erode and drill the formation while the fluid leaving the backward nozzles is used to push the nozzle forward and to widen the laterals drilled (Abdel-Ghany et al. 2011; Cinelli andKamel 2013).The RJD process is outlined in Figs. 2 and 3 and it starts be removing the production equipment from the well. In cased holes, a cutter should be lowered to open a hole through both casing and cement while in open-hole completion, there is no need for a cutter and RJD process starts without the need for a cutter. A deflector shoe is then lowered into the well using coiled tubing unit to reach the target and oriented using gyro. The system starts circulating fluid under high pressure through the high-pressure hose and then exits the nozzle at very high speed to erode and drill laterals, push nozzles into the laterals, and widen the drilled laterals. Once lateral is drilled, pressure is decreased and hose is removed. This process can be repeated as needed to drill more laterals

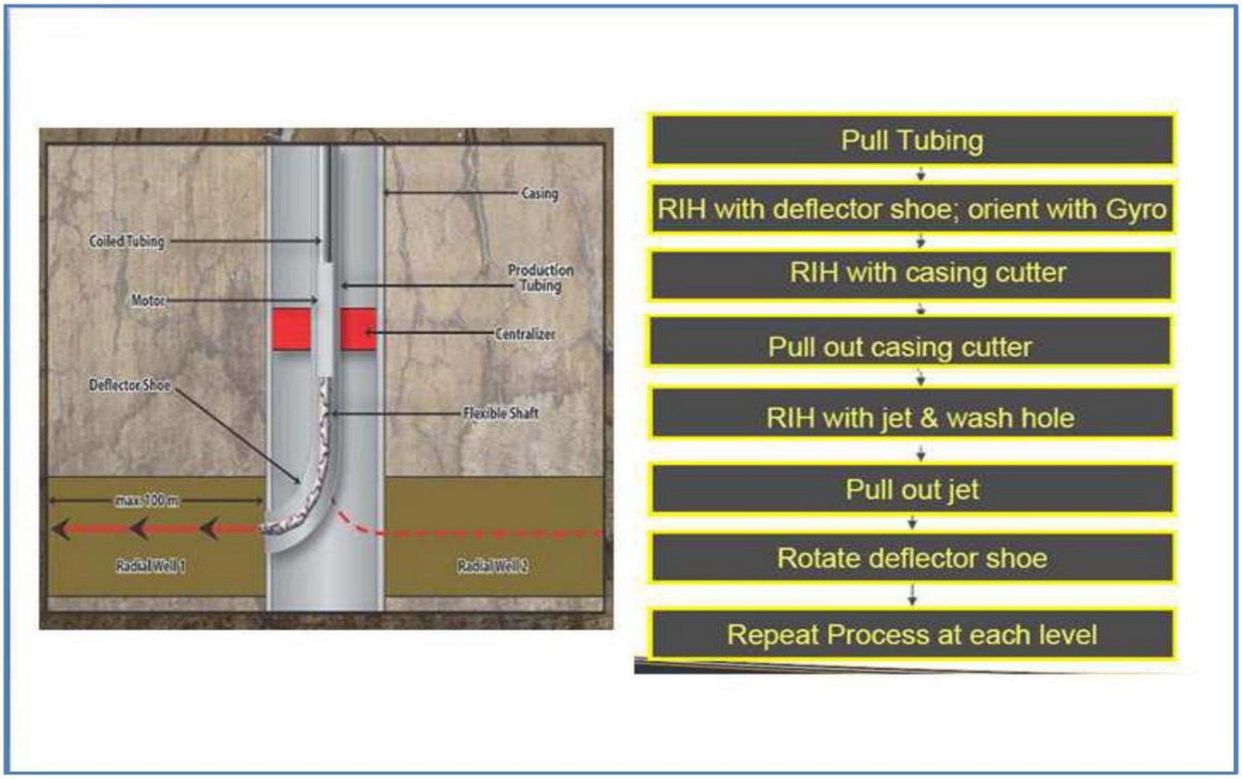


Figure 2—RJD procedure (Courtesy of RadJet).

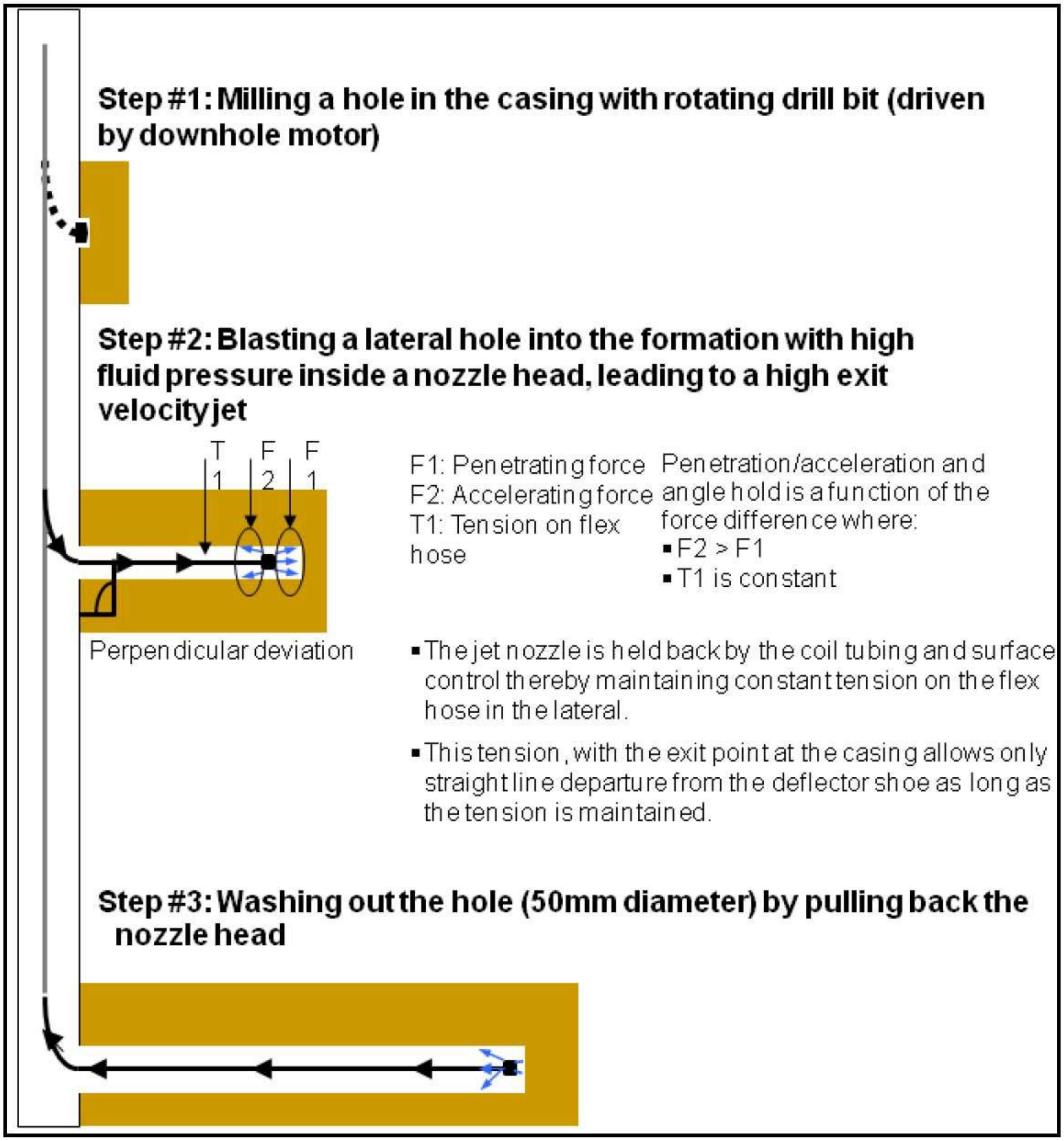
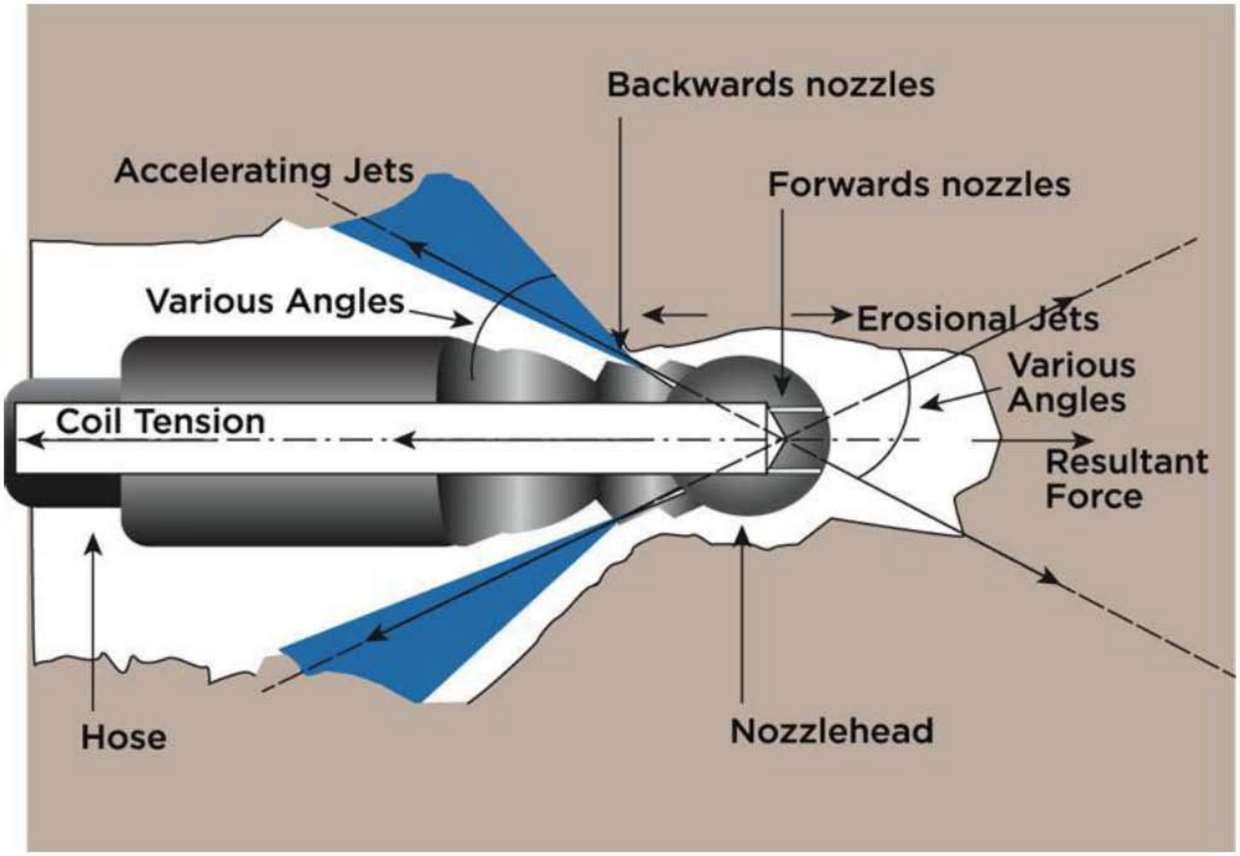


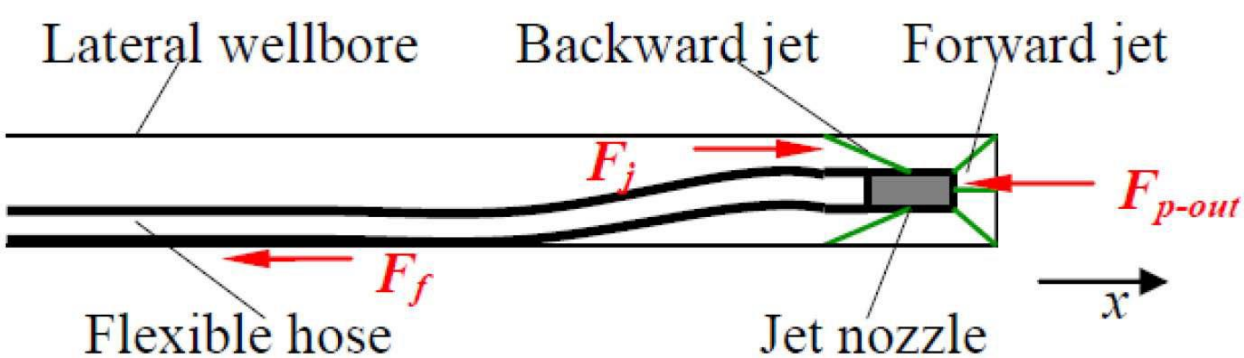
Figure 3—RJD procedure (Courtesy of RadJet).

6.3 RJD MECHANISM

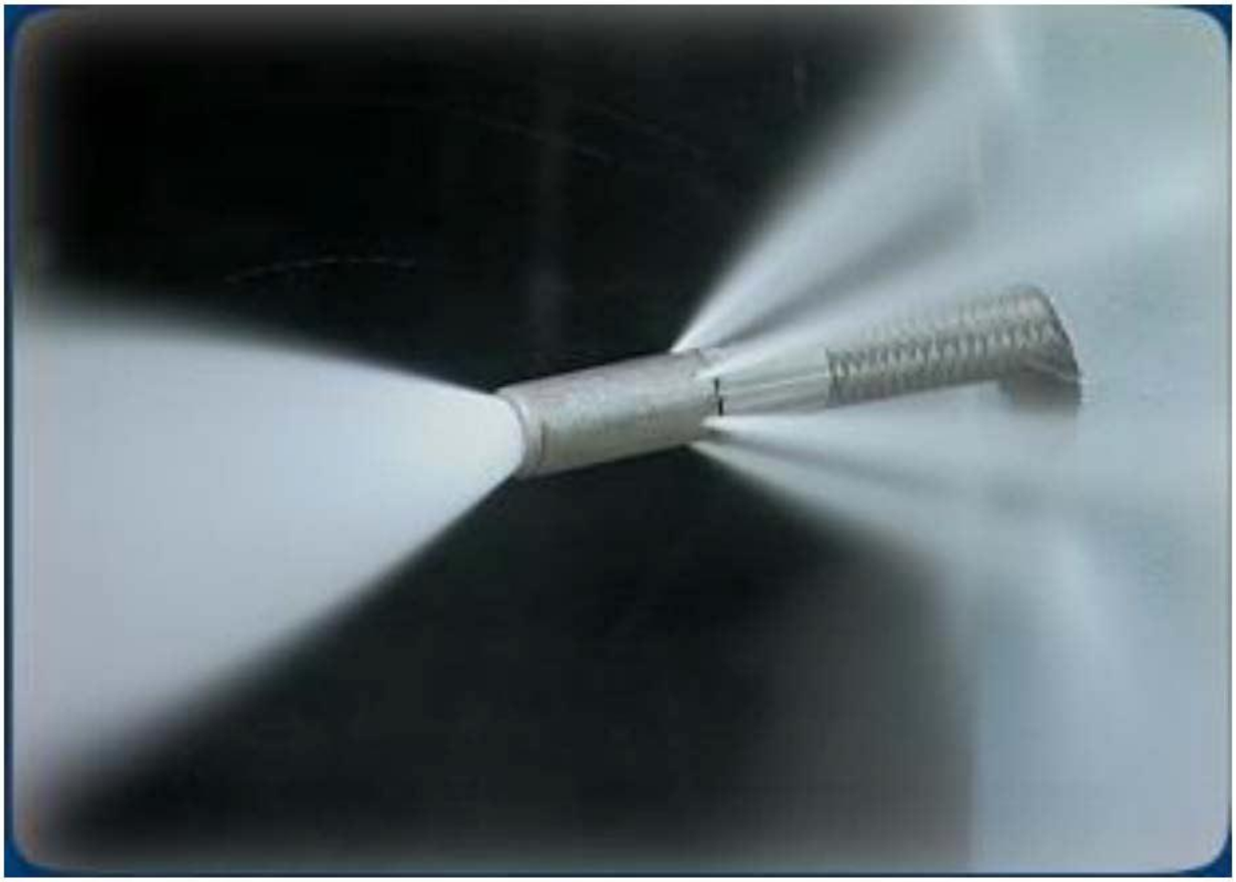
The basic cutting mechanism is by using an array of nozzles in a drill head. Each nozzle has jetting fluids with necessary additives running through it with very high exit velocities of 1000 fps and creating a drawdown of 10,000 psia. These high-pressure jets cut through the formation employing various penetration mechanism include superficial erosion, failure resulting from pore-elastic tension, and cavitation. As shown in Figs. 4, 5, and 6, due to the distribution of nozzles in drill head, enough force is available to let the drill head slide into the lateral perforation created by water jets. There are four forces affecting on jet nozzle and flexible hose; fluids pressure on the forward surface of jet nozzle, *Fp-out*, friction force between wellbore and deflector, *Fdf*, friction force between wellbore and flexible hose, *Ff*, and ejecting force generated by fluid jetting from orifices and acting on rocks, *Fj*.



Sketch of the Nozzle



Force Analysis of RJD System.



RJD procedure (Courtesy of RadJet).

The forces along the x-axis is then can be written as:

$$F_{pull} = F_j - F_{p-out} - F_f - F_{df} \qquad (1)$$

Fdf is insignificant when compared to other forces and therefore it is neglected. This reduces the above equation to:

$$F_{pull} = F_j - F_{p-out} - F_f \qquad (2)$$

The remaining forces are defined as follows:

$$F_j = \rho {v_0}^2 A_0 - \sum \rho {v_i}^2 \cos\varphi_i\, A_i \qquad (3)$$

$$F_{p-out} = \frac{\pi}{4} p_{out} {d_o}^2 \qquad (4)$$

$$F_f = f \rho_h g l_h \qquad (5)$$

As long as the pulling force is positive, the well can extend forward. This continues until the frictionforces increases at a certain well length, *ldh*which results in a zero value for pulling force. At this point, the well cannot extend anymore and the well has reached its maximum length

6.4 RJD TOOLS

Holes in casing and cement can be drilled using several techniques from cutter to energized fluid containing abrasive materials. The jetting nozzle is normally between ½-in. and ¾-in. in diameter with a length of 1.0-
in. and contains number of forward orifices to allow fluid to drill through formation and backward orifices to allow fluid to widen the lateral and push the nozzle forward (Dickinson et al. 1992; Cinelli and Kamel 2013).The hardware used are bottom hole assembly consisting of casing cutter, small diameter bit, mud motor,hydraulic piston along with auxiliary tools of tubing end connector, anchor, orienter, steering tool, controller,Fig. 7. In addition, a coil tubing unit is use to convey the drilling process from the surface (Kobar and Gogoi2014). The equipment connection diagram is shown in Fig. 8 (Gang et al. 2013).

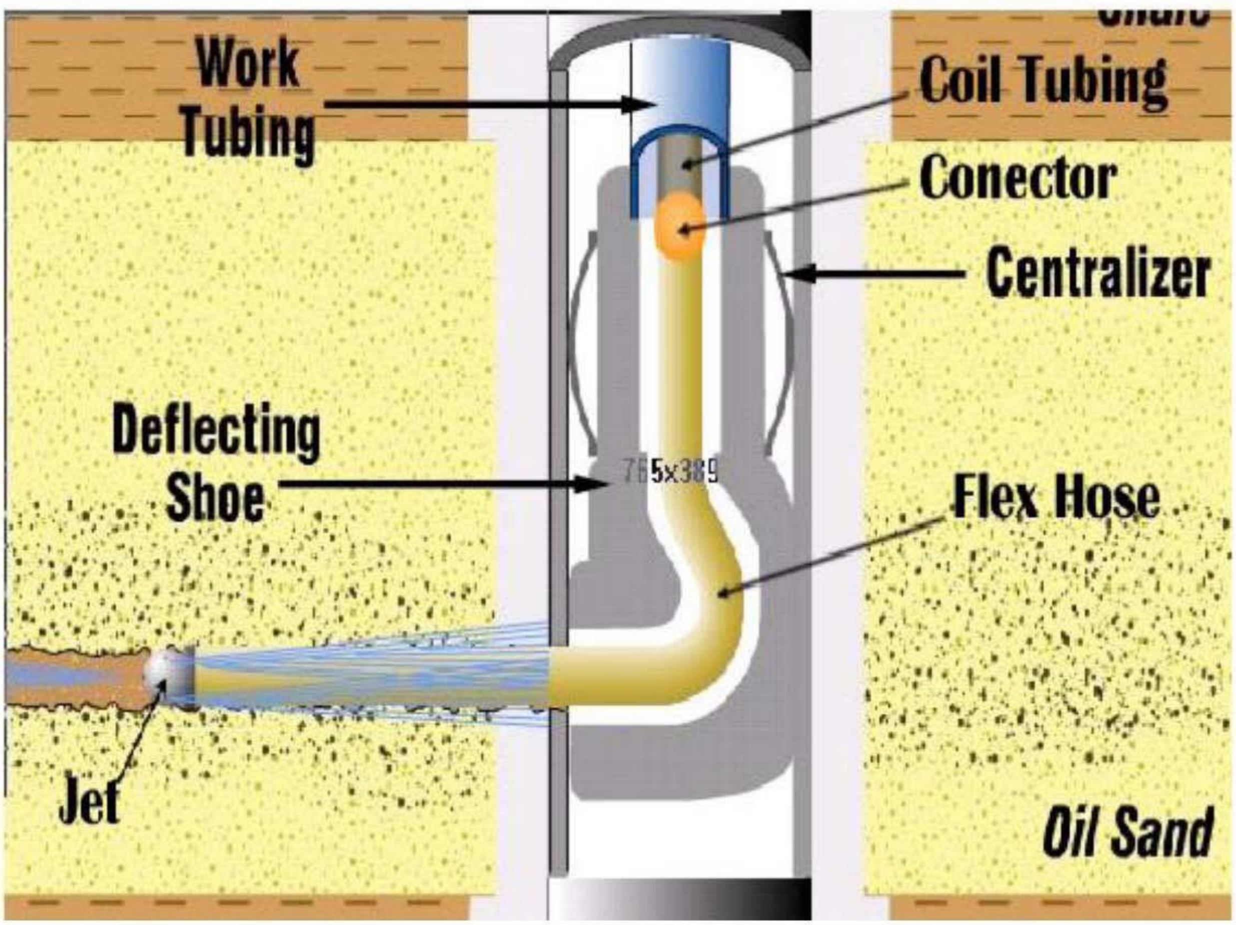


Figure 7—RJD Downhole equipment

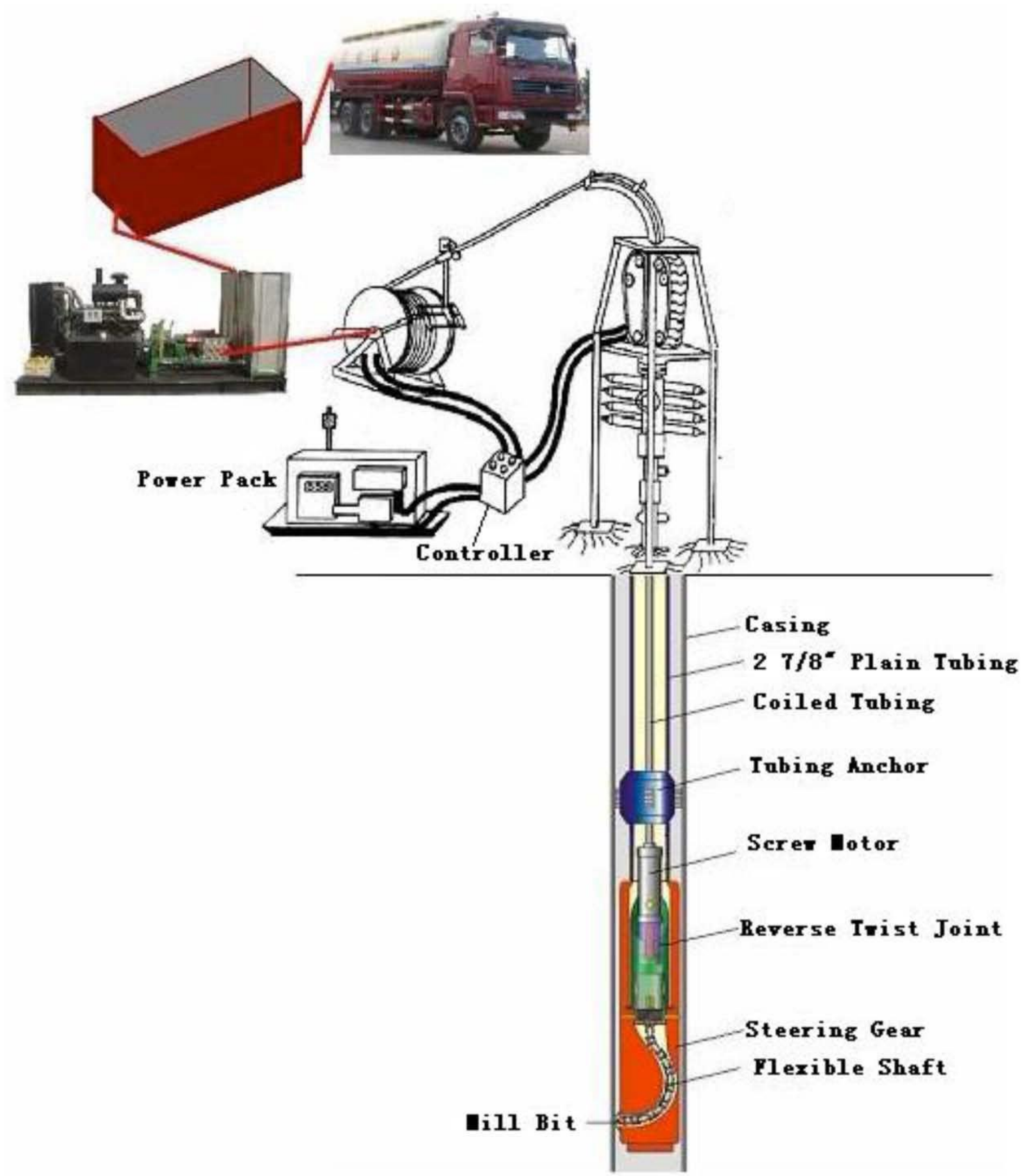


Figure 8—Equipment connection diagram.

6.5 RJD FLUIDS

In RJD process, fluids with abrasive particles, or grains, are circulated against the surface so that each particle cuts away a small bit of material. The fluid generally, has an important indirect role. It stores and transfers the energy required to accelerate abrasive particles, guides the abrasive particles and focuses impacts within a small spot, flushes debris and abrasive particles away from the working zone, and ensures that fresh surface material is always exposed. In addition, it provides some lubrication between the particle and formation, reduces frictional heating, and provides an effective convection-cooling medium, where heatgenerated during deformation is immediately extracted from the formation (Al-Marahleh 2015).
Cinelli and Kamel (2013) discussed the RJD fluids in details. Briefly, in RJD process, various fluids can be used and the candidate fluid depends on both formation rock and fluids properties. Water is considered the most common RJD fluid, as its advantages over other fluids are obvious. In cases where water is not an option, like water-sensitive formations, diesel is a viable alternative to avoid swelling problems.It also enhance penetration rate due to its solvent properties, especially with paraffinic crude oils. Acids like hydrochloric acid are good candidates for carbonate formations as it reacts and dissolves carbonateformations.

Hydraulics

Ben et al. (2016) discussed the hydraulics of RJD using a full-scale experimental system. The required pump pressure for RJD operations at the optimum flow for specific well configuration can be calculated as:

$$\Delta P_{pump} = \Delta P_{CT} + \Delta P_{ST} + \Delta P_{hose} + \Delta P_{bit} \tag{6}$$

For friction pressure losses calculations in either coiled tubing section or straight tubing section, Darcy-Weisbach equation can be used with the appropriate friction factor formula:

$$\Delta P_{CT} \; or \; \Delta P_{ST} = \frac{f_f \rho l_t v^2}{d_i} \tag{7}$$

The pressure losses in the flexible hose, considering its materials and specifications, Ben et al (2016)proposed the following equation.

$$\Delta P_{hose} = \alpha \rho^{0.75} \mu^{0.25} \frac{l_h Q^{1.75}}{d_h^{4.75}} \tag{8}$$

For pressure losses through jet bit, the following equation can be used:

$$\Delta P_{bit} = \frac{0.5136 \rho Q^2}{C^2 A_i^2} \quad (9)$$

The proposed hydraulic model was reasonably comparable to field data and the pressure losses through flexible hose and jet bit represent the major components in system pressure losses (41% and 56%,respectively). A detailed hydraulics calculation model and optimization procedure was presented in this research article (Ben et al. 2016).

6.6 APPLICATIONS OF RJD

The ability of an abrasive assisted water jet to cut through rocks and metals has potential applications in the oilfield. In oil and gas industry, radial jet can be used to increase the drainage surface area and enhance oil production. In drilling, the high- pressure jet-drilling system can dramatically reduce the torque and thrust required for drilling, thereby increasing reliability, drilling rate of penetration (ROP), and lateral reach, which eventually reduces drilling cost.

In general, the main application of RJD is to provide a fast and economical method to recover the remaining hydrocarbons form marginal or mature oil and gas fields. RJD has been proven to enhance production rates, reduce decline rates and prolongs the productive life of wells and fields, reduce near wellbore damage and/or by-pass damaged zones, allow connection with vertical permeability channels.It is also a viable alternative for traditional perforating to extend beyond near wellbore damaged zone, when other stimulation techniques are not applicable, an alternative for layered formations and when close to water contact (Ragab 2013).

This technique can be applied in different disciplines in oil well industry such as:

1. Well completions
2. Well stimulations
3. Directed reservoir treatment
4. Improve water injection
5. Improve vertical cleaning
6. Reduce water coning
7. New wells instead of standard completion methods
8. Water disposal and re-injection
9. Steam applications in heavy oil and tar sands.

6.7 ADVANTAGES OF RJD

Radial Drilling is characterized by small footprint and minimizes the formation damage and it can be used as a replacement for well stimulation through laterals and for cost reduction by minimizing the logging expense. RJD is economical: it can be a cost effective method to complete vertical wells to perform likean open hole horizontal completion.

In addition and based on what have been performed on some worldwide fields, the radial drilling methods have some economical and technical benefits such as (Dickinson-Dickinson 1985; Bruni et al. 2007):

1. Radial drilling penetration greatly exceeds conventional (perforation) penetration and can reach substantially beyond the damaged area of the well bore.
2. Laterals can be jetted through tubing, eliminating the need for pulling the production tubing.
3. Reach beyond the damaged area of the well bore. It can penetrate up to 300 feet, in up to 16 different directions.
4. No need for large, expensive rotary rigs.
5. Does not require mud pits that can damage the environment.
6. No casing m illing requirement, therefore no need to circulate mud back to the surface.
7. No additional stimulation required.
8. The process is fast, average operation duration is two days per well (can drill up to eight laterals in
only two days), so no big loss in production.
9. No logging expense is required.
10. No need to change well-bore configuration.

6.8 LIMITATIONS OF RJD

RJD principal applications to date have been in marginal and mature fields with low productivity and shallow depths. At present, this method can only be applied in vertical or near vertical wells. Its application in deviated and horizontal wells is still under investigation. Based on the previous operations using radial drilling all over the world, there are some limitations and challenges in applying such technique in oil and gas wells. Among these limitations are (Abdel-Ghany et al. 2011; Elliott 2011):

1. Difficulties of penetration under porosity of 3 to 4%.
2. Maximum working depth about 4000 - 9000 ft.
3. Bottom hole temperature not to exceed 120°C (248°F).
4. Maximum wellbore inclination 30° and no more than 15° at the zone target depth/zone of interest.

5. Maximum tensile strength 100,000 psi.
6. There is no way to complete the lateral with a liner.
7. Reentering the lateral after it has been drilled could be very tricky.
8. There are no surveillance options inside the lateral.
9. Standard logging tools likely will not fit into the lateral.
10. Directional control of the lateral is also very difficult.
11. Laterals can prematurely terminate due to fractures, faults, or other reservoir heterogeneities.

Chapter 7

MODERN APPLICATION OF FISHBONE DRILLING

Slotted Liner Sheathing Coiled Tubing Fishbone Jet Drilling: An EfficientApproach for Coalbed Methane Recovery

Unconventional resources, such as shale gas, tight oil, and coalbed methane, are making a significant contribution to the world energy. Coalbed Methane (CBM) reservoirs are naturally fractured formations, comprising both permeable fractures and matrix blocks. Owing to large drainage area, multilateral wells are an efficient way of exploiting CBM reservoirs, particularly for coalbeds with extremely low permeability and low compressive strength, where hydraulic fracturing is ineffective. The fishbones technology is a new well stimulation technique developed to increase well production performance and improve the connectivity between the reservoir and the well; it is an alternative to hydraulic fracturing. The fishbone well is defined as a series of multilateral well segments trunking off a main horizontal well. The appearance of this kind of multilateral wells closely resembles the ribs of a fish skeleton trunking off the main backbone.

The major advantages of this technology over hydraulic fracturing are the competitive price and the reduced operation time."Slotted Liner Sheathing Coiled Tubing" (SLSCT) is a new concept for multilateral drilling . This technique integrates coiled tubing jet drilling and slotted liner completion into one step by eliminating the process of tripping out drill strings after drilling laterals. The slotted liner conveyed by coiled tubing and the bottom hole assembly (BHA) are designed to create a number of laterals at a certain angle to the mother well. Being cost effective and capable of protecting borehole from collapsing, SLSCT drilling provides a practical way for drilling fishbones in coalbed methane reservoirs. Laboratory experiment has been conducted to examine the feasibility of the technique in terms of the tubular friction performance; critical downhole tools such as deflector, separator and slotted liner are designed comprehensively. However, all these designing of tools haven't taken the effects of fishbone well patterns on gas and water production performance into consideration. Furthermore, the fishbones are jet-drilled multilaterals by high pressure water jet; the study of jet drilling tools are still lacking. Therefore, there are gaps in the research for the optimum design of critical tools in SLSCT drilling considering the enhancement of well production performance.

Nelson et al. (2000) pointed out that the major problem in most CBM development is not ability to produce commercial quantities of gas from reservoir. Therefore, the use of low-cost, innovative drilling and completion methods has been a critical factor in making the CBM play economical. SLSCT fishbone jet drilling appears to be a promising technique in CBM development; there may be a cost/benefit that further research could uncover. In order to evaluate the efficiency of fishbone wells in coalbed methane, reliable production performance estimation methods are needed. Construction of a complete theory of coal well deliverability is difficult as it is necessary to consider the two-phase flow of gas and water in the coalbed. However, coal wells produce substantial amounts of water before the reservoir pressure declines to the desorption pressure. Once the drainage area of a coal well has dewatered and the gas rate peaked, water production often declines to negligible rates. Most of the productivity prediction for fishbones or multilateral wells are based on numerical models.

Maricic et al. (2008) studied the horizontal and several multilateral drilling patterns for CBM reservoirs by use of commercial reservoir simulator based on a dual-porosity model with matrix-tofracture and fracture-to-fracture flow calculations.

Freyer and Shaoul (2011) modeled the fish bones using a 3D reservoir simulator and computational fluid dynamics (CFD). These methods are efficient in modeling fishbone production performance. However, most of them are very complicated due to gridding issues and expensive computational cost.

Cavalcante Filho et al. 2015 simulated the performance of fishbones by extending the Embedded Discrete Fracture Model (EDFM). The authors treated each fishbone branch as a fracture with dimensions equivalent to the branch dimensions. This has been shown to be a numerically efficient approach. However, a preprocessing code is often needed to connect the fishbones to the fracture network into a data set for the simulator, which is challenging to apply due to complexities of development of the computational codes. In this study, we extend the semi-analtyical model for modeling gas and water two-phase flow with complex fracture networks in CBM wells developed by Yang et al. (2016) to model fishbones. We assume that fishbones are modeled as fractures because of their smaller diameter and length.In this paper, we first introduce the process of SLSCT drilling, and then we optimize fishbone well patterns by extending the semi-analytical model. Sensitivity analyses are made to verify the importance of lateral parameters. Based on production performance results, the deflector and jet drilling tools are designed.Laboratory rock breaking experiments are conducted to further assist designing of jet drilling bits and jetting conditions. The overall objective of this study is to provide a cost effective stimulation method fordeveloping CBM reservoirs.

7.1 SLSCT DRILLING PROCESS

Slotted liner sheathing coiled tubing (SLSCT) drilling is a novel technique designed to synchronize the drilling and completion job in one trip (Yang et al. 2015). A slotted liner, sheathing around coiled tubing,
is designed to run into the well and complete the laterals (Fig. 1). The laterals are jet penetrated by high pressure water jet. When the target depth is reached, a steel ball is dropped with the drilling fluid and pumped down the coiled tubing, landing on the ball seat. Then, enhancing the pressure inside of the coiled tubing up to a desired critical value, the pins located on the separator (a ball seat) will be cut off, after which the coiled tubing is released from the slotted liner and retrieved to the surface, leaving the slotted liner in the wellbore to protect the coal formation from collapsing. The operational procedure is as follows:

- Step 1: Lower the tubing and deflector into the mother well (horizontal section); anchor thedeflector to the end of the tubing. Calibrate the depth of the tubing and correct the orientation ofthe deflector.
- Step 2: Attach the tubing to the casing wall via an anchor.
- Step 3: Run the drilling assembly, including the jet bit, separator, slotted liner, and coiled tubing,through the tubing, and pass it through the deflector.
- Step 4: Mill a window in the casing using a high-pressure abrasive water jet.
- Step 5: Jet a lateral into the formation.
- Step 6: Drop a steel ball into the coiled tubing from the wellhead, go down with the drilling fluid at low pump rate, until it lands on the separator. Increase the pressure inside the coiled tubing, cut off the pin, release the coiled tubing from the slotted liner and retrieve it to the surface, leaving the slotted liner in the lateral.
- Step 7: Reposition the tubing anchor and deflector; repeat steps 3–6 to complete the next lateral.

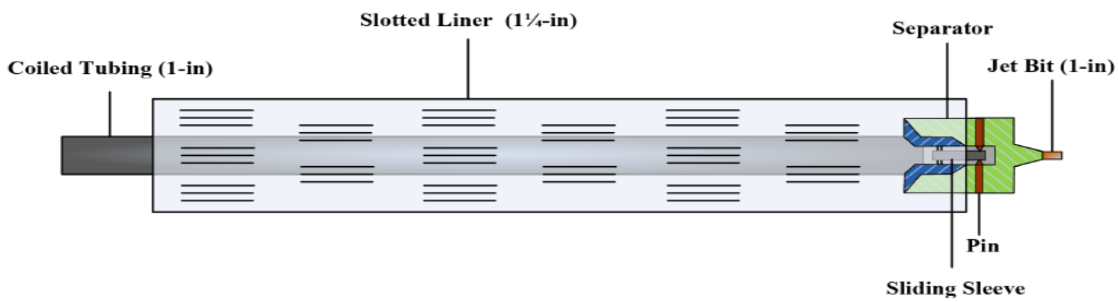


Figure 1—Downhole assembly of SLSCT drilling

In this study, the drilling assembly is designed based on a casing size of 5½ -in for the mother well, which is a commonly used casing size in the field cases. The laterals are jet-drilled with a 1¼-in polyvinyl chloride (PVC) slotted liner sheathing 1-in coiled tubing, and the outer diameter of the jet bit is 1-in. Laboratory tubular friction experiment (Yang et al. 2015) shows that PVC slotted liner could help the coiled tubing pass through the deflector smoothly and achieve drilling assembly turning from the main wellbore to the laterals. Furthermore, an increase in the internal pressure of the coiled tubing can help drive the drilling assembly forward through the deflector more smoothly. This indicates that it is viable to use high-pressure water jets to penetrate the rocks.

7.2 Fishbone patterns optimization

7.2.1 Methodology

The semi-analytical model for simulating coalbed methane production performance developed by Yang etal. (2016) is modified to account for fishbones. The fishbones' laterals are treated as equivalent fractures with same flowing properties (Cavalcante Filho et al. 2015) (Fig. 2). The relationship between fishbone laterals and equivalent fractures is defined as

$$w_f \times h_f = \frac{\pi D_l^2}{4}, \quad (1)$$

where *wf*is the equivalent fracture width, *hf* is the equivalent fracture height, and *Dl* is the lateral innerdiameter.

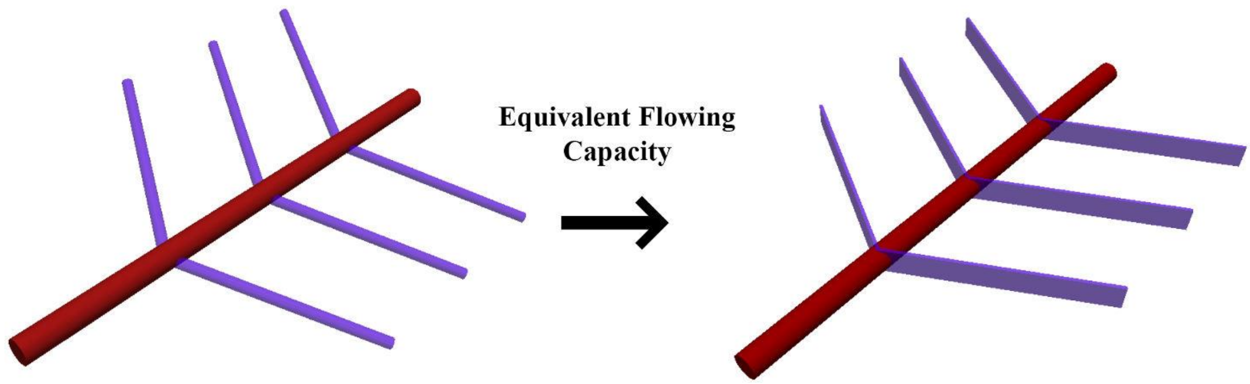


Figure 2—Model fishbones as equivalent fractures.

The model combines an analytical solution for gas and water flow from matrix to laterals with a numerical solution on the discretized lateral segments. Nodal analysis is used to discretize the fishbone lateral segments into several small segments (Fig. 3). The critical gas flow mechanisms such as desorption and moleculardiffusion are incorporated in the model. The superposition principle is utilized to consider the interactions between lateral segments. Source and sink terms of water phase are introduced to consider the water support from matrix and cleat system. Water and gas saturations are updated iteratively. Hence, the relative permeability to gas and water and capillary pressure for each lateral segment arecorrected iteratively with reservoir depletion.

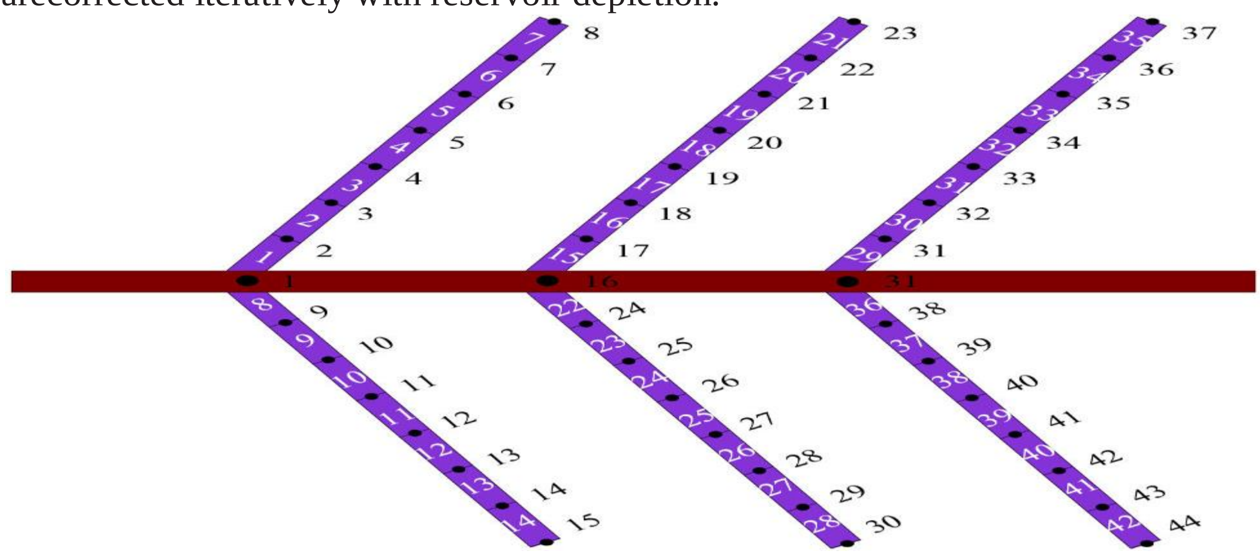
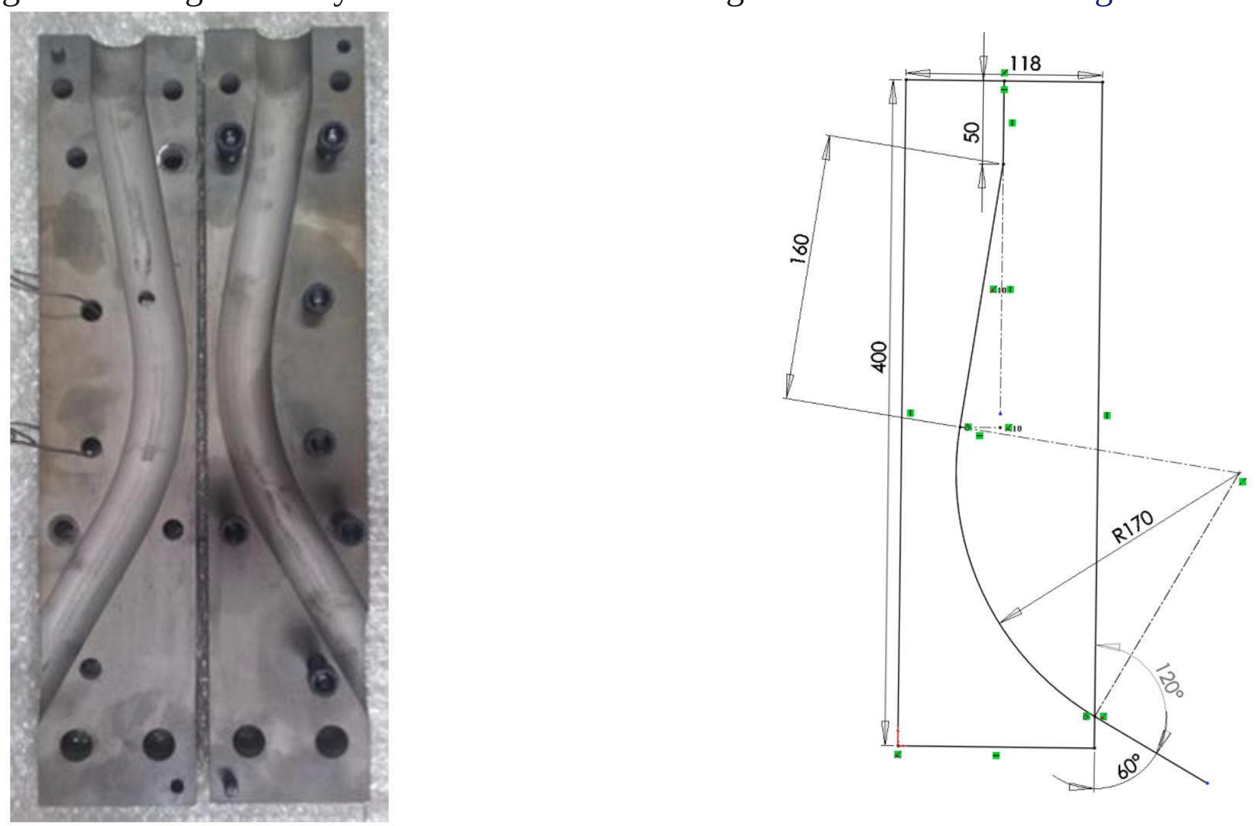


Figure 3—Discretization of the fishbones (equivalent fracture) for the Semi-analytical Model. The wellbore is in the middle of the figure (red color). The fishbones are discretized into 44 nodes (indexed in black) and 42 segments (indexed in white).

7.3 Deflector Design

The deflector is the critical tool to guide the coiled tubing from the main wellbore to the laterals, enabling the jetting bit to penetrate laterals at various angles to the mother well. The above study shows that the
production performance is enhanced with the increase of lateral angle and the water production performance remains negligible change with different lateral angles. On the other hand, tubular friction will be increased with the growth of the lateral angle, because of the difficulty of drilling assembly to pass through the deflector. Considering a balance between the gas production performance and tubular friction, lateral angle of 45–60° is the viable option. A deflector that could guide drilling assembly to create laterals with angle of 60° is shown in Fig. 9.



(a) (b)

Figure 9—Deflector in SLSCT drilling: (a) deflector used in the laboratory experiment (Yang et al. 2015); (b) deflector design with a 60° exit angle (unit: mm).

7.4 JET DRILLING TOOL DESIGN

The laterals are drilled by means of jet-impact when pumping fluid at high pressure through nozzles (Wanget al. 2016). The jet bit is designed based on gas and water production performance and ease of operation.

7.5 STRUCTURE OF THE JET BIT

To drill a lateral of adequate size and depth, a combined straight/swirling jet bit is employed, because it combines the advantages of both round straight jets and swirling jets (Liao et al. 2013; Ma et al. 2013;William et al. 2003). The jet bit mainly contains three parts: main body (Fig. 10a), extension cap (Fig. 10b),which is used to limit the radius of swirling fluid discharged from the nozzle, and impeller with a central hole and three helical grooves (Fig. 10c), which can be used for generating swirling motion of jet. The outer diameter $D1$ is 25.4 mm, the key structural parameters were designed based on the optimal results obtained by Ma et al. (2011) and Liao et al. (2013): $L3 = 1.5d1$, $L4 = 4d1$, $L5 = 3d1$, $d4 = (0.8 – 1)d1$, $\beta = 75°$, $\gamma = 120°$. The other two dominant parameters are the nozzle diameter $d1$ and diffusion angle α needing further optimization to serve the special purpose in this drilling system.

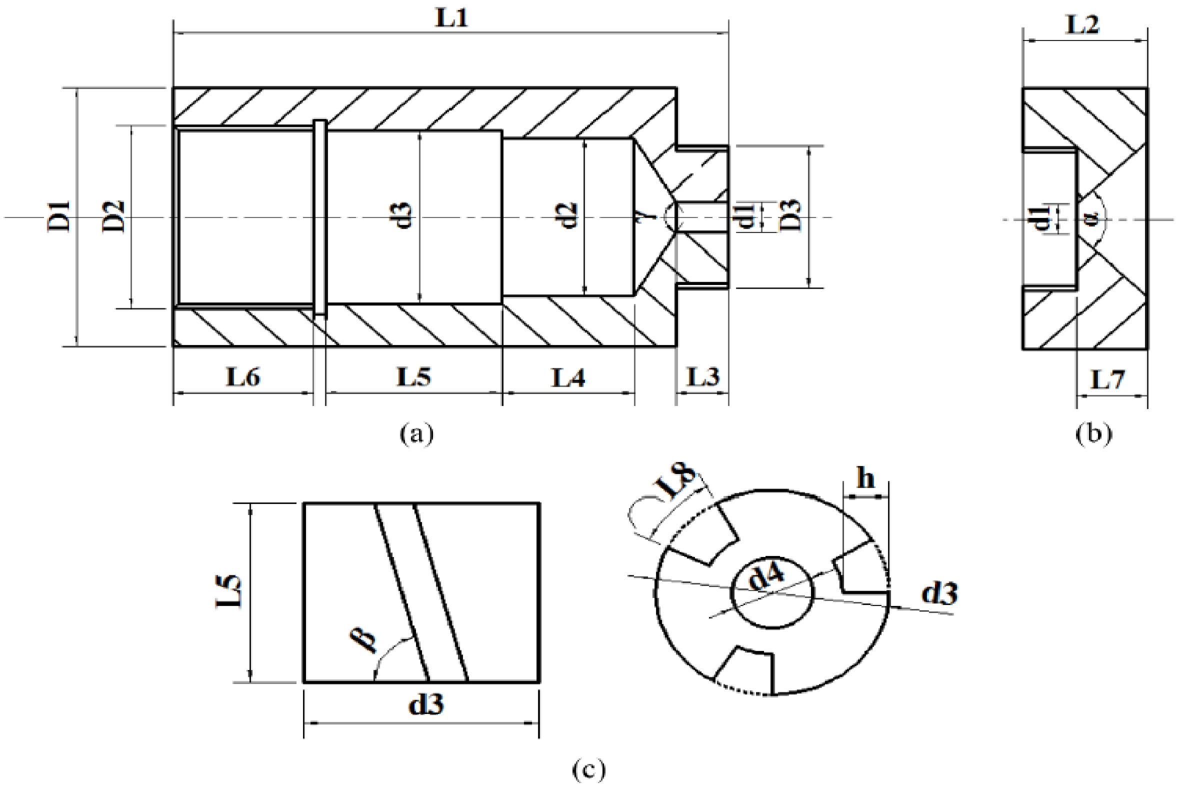


Figure 10—Structure diagram of the jet bit. (a) Main body; (b) extension cap; (c) impeller. *L1*, body length; *L2*, extension cap length; *L3*, nozzle length; *L4*, mixing chamber length; *L5*, impeller length, *L6*, screw length; *L7*, diffusion portion length; *L8*, slot width; *D1*, body outer diameter; *D2* back chamber diameter; *D3* nozzle head diameter; *d1*, nozzle diameter; *d2*, mixing chamber diameter; *d3*, impeller diameter; *d4*, central orifice diameter; *h*, slot deepth; α, diffusion angle; β, slot angle; γ, chamber angle.

Jetting condition
Two important operation parameters for high pressure water jet penetration are standoff distance and jet pressure. Standoff distance is the distance between the exit of the nozzle and the core sample, which can be neither too long nor too short. This is because the jet cannot develop fully with a shorter standoff distance; while, if the standoff distance is too long, much hydraulic energy of the jet will be lost. Jet pressure is pump pressure minus the pressure loss on the pipeline. The jet pressure also has an optimal value. Because lower jet pressure results in lower ability for breaking rocks; higher jet pressure may cause the burst of pipeline or collapse of the formation. Therefore, the optimum standoff distance and the jet pressure of the jet bit are supposed to be studied. In this paper, we optimize the parameters through laboratory experiments.

Rock breaking experiment

According to the tubular design for the technique (Yang et al. 2015), the outer diameter of slotted liner was 38mm; considering the cuttings cleaning efficiency in the annulus between the slotted liner and wellbore,the minimum size of the wellbore would be 60 mm. Thus the purpose of this test was to find suitable jet bit structural parameters and viable operation condition.

7.6 Jet bits

- The material of the jet bit is steel.
- The nozzle diameter is $d1$ = 3, 4, 5 mm and
- The diffusion angle isα = 40, 60, 90,120°.

Figure 11—The jet bits used in the laboratory experiment.

Rock samples

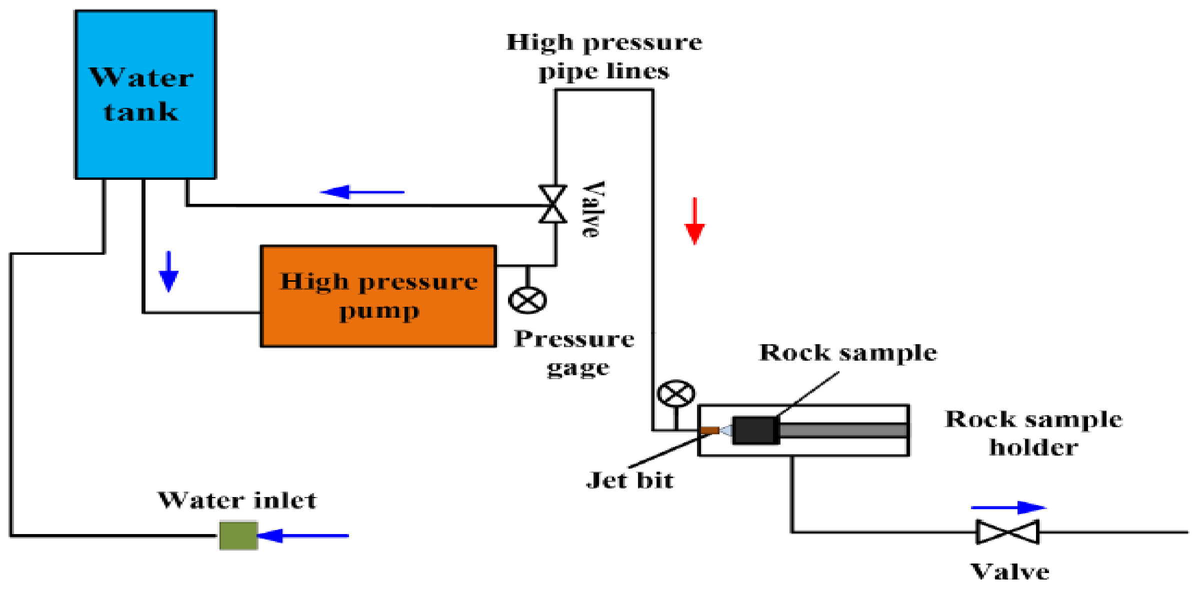
Two kinds of artificial rock samples (sandstone and coal) were used in the experiments. The sandstone samples were made by the mixture of quartz (particle diameter is 0.3–0.8mm) and cement. The coal samples were made by the mixture of coal particles and cement. The preparation procedure of the sandstone rock samples is as follows:

- Mix the quartz, cement stone and water as a volume fraction ratio of 3:2:1.
- Stir the mortar uniformly. After 5 minutes standing, pour the mortar into the plastic cylindrical molds (100 mm length, 110 mm outer diameter, 3.2 mm wall thickness).
- Wait on cement at the room temperature, avoiding sun exposure. Water the samples every two days to enhance their strength.
- Maintain the samples for 28 days, and then they were ready to test.

The coal rock samples were made by the same process, except that the ratio of coal particles to cement stone was 2.5. Rock mechanic properties of five random selected samples for each type were tested before the experiment, and the average values are presented in Table 3.

Experimental apparatus for rock breaking by jetting tools.

Schematic of the rock breakingexperiment.



Experimental results and discussion

Sandstone rock

Before the experiment is carried out, the feasibility of the impeller used to impart the swirling jet should be figured out, including its swirling effect and pressure loss. Two tests for jet bit with and without impeller were performed, respectively. The nozzle diameter was 5mm, the diffusion angle was 40°, the jet pressure was 25 MPa, and the standoff distance was 30 mm. The rock sample was sandstone. The pressure loss was measured by the nozzle flow coefficient, given by

$$C = \sqrt{\frac{513.559 Q^2 \rho}{A^2 P_j}},$$

Where,

Q is the flowrate,

ρ is the fluid density,

A is the nozzle cross area

Pj is the jet pressure.

CONCLUSION

Fishbone drlling plays a very important role in the production of hydrocarbons. Multilateral wells branching off from a single horizontal wellbore-giving the well a shape like a fish skeleton,precisely the reason or it being called a “fishbone”well.This construction allows significantly greater coverage of oil-saturated sections of the strata in comparison with traditional horizontal wells whil,at the same time,involving less extensive drilling works than are required in creating a multistage well.The fishbone construction allows each of the branches[laterals] to be directed at separate reservoirs,without having to encroach on adjacent strata with either water or gas.The laterals can extend in any direction from the horizontal wellbore,at significantly lower cost than drilling individual wells-althoughthe process of drilling fishbone wells is,itself,significantly more complex. The fishbone wells are new production technology applied to increase well productivity and access the difficult geological formations and unconventional reservoirs. The main advantages of this technology over hydraulic fracturing are the competitive price and reduced operation time.Increase productivity by connecting the well to the reservoir with up to 300 laterals.Accelerate production by integrating stimulation in your drilling program.Avoid water or unwanted gas by predictable penetration and location of the laterals.Simplify logistics by using rig pumps and significantly less fluids.Accelerate progress by avoiding cementing, perforating, cleanouts, running frac strings and other operations.Reduce HSE exposure by reducing the number of operations and man-hours. Reduce the environmental impact by reducing emissions and by using less fluids.Avoid flow back and disposal of fluid from hydraulic fracturing.Effective reservoir conductivity may be low due to layering or faulting. The layers or faults can be penetrated and drained by Fishbones with the mother bore not even penetrating the faults.Different intervals have different pressures and can be hard to effectively hydraulically stimulate. Fishbones allows you to stimulate zones with different pressure regimes.Thus we are opting fishbone drilling as an alternative to fracturing.

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