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Applications of Underbalanced Fishbone Drilling for Improved Recovery and Reduced Carbon Footprint in Unconventional Plays

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Abstract

Fishbone Drilling (FbD) consists of drilling several micro-holes in different directions from the main vertical or deviated wellbore. Similar to multilateral micro-hole drilling, FbD may be used to enhance hydrocarbon production in naturally fractured formations or in refracturing operations by interconnecting the existing natural fractures. When combined with underbalanced drilling using a coiled tubing rig, FbD enhances the production further by easing the natural flow of the hydrocarbon from the reservoir to the wellbore. The design aspects of the Fishbones include determining the number, length, distance between the branches, and the angle of sidetracking of the branches from the main borehole. In addition, the design of efficient drill string components to suit the FbD conditions are another important design aspect in FbD technology development. Examples of this include a high-performance small, diameter downhole motor and the use of High Voltage Pulsed Discharge (HVPD) plasma shock waves at different pulse frequencies and wave pressures to impose shear forces on the formation to break it more easily. This paper will present a comprehensive review of the FbD technology, including some of its current applications and design aspects. The possibility of using FbD in conjunction with hydraulic fracturing to boost production by creating a network of connected fractures will be discussed, and some of its technical and economic benefits and challenges will be compared.

Keywords: Fishbone Drilling; Underbalanced Drilling; Coiled Tubing; Unconventional Plays; Downhole Motor; Plasma Shock Wave

Introduction

Multilateral wells are one of the recent technologies in drilling laterals into the reservoir sections in order to improve the recovery. Horizontal multilateral drilling is a common technology for field development in unconventional plays. Multilateral drilling is defined as a main well with multiple sidetracks and branches in different directions [1]. This type of well design depends on many factors, mainly the geological, petrophysical, and geomechanical properties of the reservoir formation. Multilateral drilling aims to increase reservoir production by expanding access to larger production zones and increasing the contact area between the wellbore and formation [2]. The micro-hole that trunk off from the main horizontal well is called a Fishbone [3]. The name is discovered from the drilling shape of the Fishbone well design, which looks like a fish skeleton. Every single Fishbone micro-bore hole drilling penetrates in the same way as a multilateral well drilling operation. The micro-bore hole is manipulated by multiple parameters, including the length and number of the micro-bore hole, the angle of inclination, and the distance between each kickoff point of deviation. Generally, the multilateral well is drilled from a main vertical borehole. In contrast, the micro-bore hole in an FbD technique is drilled from the multilateral wells, and connected to the lateral section of the well [4].

Drilling multilateral using coiled tubing results in several advantages [5]. The oil and gas market fluctuation encourages the industry to move forward to more appropriate, accessible, and less costly technologies, including coiled tubing rigs [6]. Coiled Tubing Drilling (CTD) technology has been practiced worldwide in the last three decades for different workover and stimulation applications [7]. CTD provides hydraulic horsepower through its continuous string to transfer power to the bottom-hole assembly. The CTD performance is a function of multiple factors such as the excellent path design to provide all kinds of stuck and buckling, the open hole diameter mainly less than 2⅝ inches, the length, diameter of the existing casing, drilling fluid physical and rheological properties, total depth of the well and the weight on bit [8]. Under-Balanced Drilling (UBD) in shale plays in the United States is becoming a preferred technology [9]. In this drilling method, the drilling mud hydrostatic pressure is less than the reservoir pore pressure [10]. This will prevent reservoir damage and contamination due to the penetration of the drilling fluids into the reservoir, resulting in a positive skin factor [11]. The wellhead pressure is controlled through surface facilities during UBD operation to control the annulus pressure and prevent possible blowouts.

The study of naturally fractured reservoirs is very challenging, with the main complexity being how to characterize and predict the fracture networks in the subsurface [12]. Advanced 3D seismic technics, such as seismic attributes and specific well log data such as borehole imagery and acoustic sonic, help to detect and model the fractures at reservoir and field scales [13]. These technics have helped to enhance the understanding of the impact of natural fractures on fluid flow, where the drainage of the matrix is more effective due to a high density of fractures and good connectivity. The studies of unconventional reservoirs have rapidly grown over the last years, and a significant increase in oil and gas discoveries where natural fractures play a substantial role in the production [14]. During the field development, wells are drilled based on the spatial distribution of natural fractures in conjunction with the geometrical and geomechanical parameters, such as the orientation of fracture planes and the maximum horizontal stress [15]. In many fields worldwide, most siliciclastic and carbonate reservoirs are fractured. In unconventional plays, the preference is to intersect the areas with high natural fracture density (sweet spots) to induce the fractures and stimulate the reservoirs [16]. While drilling into fractured zones is beneficial in terms of production enhancement, it introduces several drilling-related challenges [17,18]. From a drilling perspective, the goal is to interconnect the existing fractures and increase the flow rate with the growth of the effective permeability and the fracture network connection [19].

In the past four decades, drilling long horizontal wells has experienced significant advancements, particularly in developing unconventional reservoirs. Technologies have been developed to build high-performance drilling motors, advance well-completion methods, and introduce new logging tools and many other inventions to drill longer laterals faster and more efficiently [20]. In recent years, the Fishbone wells were introduced to the drilling industry as a new multilateral horizontal well technique due to their economic and technical advantages [21]. The significant difference between Fishbone and multilateral methods is that the Fishbone well is drilled in the same reservoir pay zone compared to the multilateral well, which tends to propose the best solution for different reservoir layers [22]. The Fishbone technology represents an ideal solution to the economic, environmental, and regulatory limitations [23].

Grigoryan, the father of multilateral well-drilling technology, demonstrated the theory of production enhancement by increasing the open-hole surface flow from wellbore branches [24]. This was shown by the famous study of well 66/45. The drilling operation, in that case, consisted of one vertical section of 1,886 feet long, nine branches in different pay zones with a length between 262 and 984 feet for each branch. Surprisingly, this well showed a 17 times increase in production rate with respect to the near offset wells, with just a 1.5 times increase in cost [25].

Hydraulic fracturing is a very common method for hydrocarbon well stimulation in unconventional reservoirs [26]. Still, the deployment of a high volume of water injection could entail some risks to the environment [27]. The primary goal in shale drilling is to create extensive fracture networks to increase the permeability of the reservoirs around the wellbore [28]. However, the experience shows that not all tight formations respond to hydraulic fracturing effectively [29]. A study conducted by Fishbones AS [30] compared Fishbones-Drilling with multi-stage Propped-Hydraulic Fracturing Operations and found no significant distinctions between the two methods up to and including the production-liner running operations. The study found that Fishbones-Drilling is appropriate for sandstone formations, which led to an appropriate sandstone enhancement approach. While Fishbones-Drilling operation includes an activation sequence and subsequent execution, Propped-Hydraulic Fracturing Stages involve an activation sequence followed by repeated multi-cycle execution stages.

Plasma Stimulation Fracturing (PSF) was developed at the Texas Technology University as an alternative technique to conventional hydraulic fracturing in 2010 [31]. As the fourth state of matter, the plasma state is an ionized gas consisting of positive and negative ions, electrons, and neutral species. The PSF technology involves inducing electrical energy to a plasma solution in a borehole to transform high-energy pulsed-power electric discharge into a high-pressure, high-temperature shock wave [32]. The plasma source expands rapidly, creating a shock wave that produces a stress field and creates multiple radial fractures in the reservoir rock. The benefits of PSF include a low source of energy costs, high well productivity, small surface facilities' footprint, and consequently, lower well stimulation costs.

A study reported by Hoque A [33] in the IADC Drilling Contractor Magazine, conducted by THREE60 Energy, found that Fishbones' CO_2 emissions were notably lower than those of other methods. The research showed that Fishbones' jetting solution resulted in a reduction of 88% in emissions, while the drilling method resulted in a 95% decrease in comparison to other options available in the market. The study indicated that Fishbones' jetting emissions were 6.7 tonnes per completion, in comparison to acid-fracturing's 53.3 tonnes. Furthermore, Fishbones' drilling emissions were 35.4 tonnes per completion, compared to propped-fracturing's 651 tonnes. The study also highlighted that Fishbones' techniques provide a safer, more environmentally friendly and potentially more cost-efficient solution for well enhancement and that its expertly controlled pumping operation allows for targeted stimulation of reservoir "sweet spots" and connection with faults and fractures.

The objective of utilizing Fishbone well geometry is to increase the drainage area of the reservoir by maximizing the reservoir contact with the branches drilled in Fishbone patterns [34]. As a result, the production rate will increase with an optimized drilling and completion cost. This theory has proven the feasibility of drilling Fishbone instead of fracking operation or as a booster to enhance the recovery of many reservoir zones [35].

This paper proposes the integrated underbalanced coiled tubing FbD as a booster method to enhance production from the unconventional reservoir. The paper reviews successful case studies worldwide and discusses this method's advantages, limitations, and new technological development needs. An assessment of the different drilling tools, production versus cost, fundamental research for productivity prediction as well as the effect of the fishbone design on the recovery has been summarized in this paper. The recommended future studies have been combined after reviewing the majority of references in the literature related to fishbone drilling technology.

Fishbone Well Design

Designing the optimized geometry of the Fishbone well path with a specific number of branches, directions, lengths, the angles between the main hole and the micro-hole, and distances between the Fishbones is a complex and challenging task, and its implementation is a relatively new technology in unconventional reservoirs [36]. The optimum design is the one that maximizes the economy of the project by enhancing well productivity as a result of increased reservoir contact [37]. However, the operational costs of FbD are likely higher than conventional drilling due to several challenges that frequently occur during such complex drilling operations. Evaluation of economic revenue in terms of productivity profit versus the drilling costs has been performed in many case studies worldwide [38].

Different researchers in detail have studied various Fishbone configurations through numerical simulations, analytical and data-driven models, and empirical correlations. The simulation methods studied the impact of the Fishbone well geometry parameters on the reservoir recovery. A summary of the results is presented in the following subsections.

Number of Branches and their Direction

Figure 1 presents the number of Fishbone branches (n) versus the oil production rate in a Middle East oil field based on three-dimensional fine-scale numerical simulations followed by sensitivity analysis (case#1). The results showed that by increasing the number of branches to four, oil production increased and then became plateaued [39]. The second case represents production versus time as a function of the number of branches from another numerical simulation study of an ultra-thin reservoir in the Daqing Peripheral oilfield [34]. Case #2 was considered the thinnest oil-drilling Fishbone well until 2012. These numerical simulations proved the same results: when the number of branches increased, the daily production increased. It appears that the number of branches is related to the reservoir volume; moreover, almost all the net pay volume is stimulated at an optimum number of branches.

While adding more branches improves production, it increases drilling costs. Consequently, the optimum number of branches is defined as the intersection point of a relatively high production rate with the minimum number of branches.

Xing, et al. [34] analyzed and optimized the effect of the orientation of the branches on Fishbone productivity, where the length of each branch was the same, but the number of branches and their directions varied. The geometries of the Fishbones for the four cases studied are as follows: (a): 4 branches on different sides and a 30˚angle between each branch and the main lateral, (b): 2 branches on the same side and a 30˚angle between each branch and the main lateral (c): 2 branches in different sides and 30˚angle between each branch and the main lateral (d): 1 branche and 30˚angle between the branch and the main lateral. The results from Xing, et al. [34] numerical simulations showed that the production increased when the branches were placed on opposite sides instead of the same. As a result, the optimum design in this case#2 was to drill four branches on the opposite sides of the main hole to ensure the maximum reservoir contact [34]. The previous results suggest that having branches on different sides will augment the stimulated volume by reaching new reservoir areas with these branches.

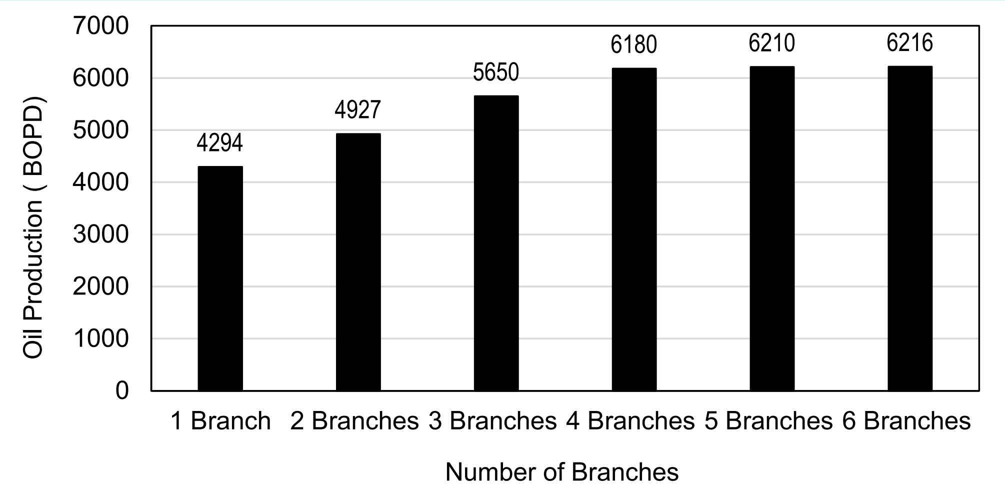

Figure 1: The effect of the number of branches in FbD on daily well production [39].

Length of Branch

In order to optimize the length of the branch (L), Manshad, et al. [39] conducted a second sensitivity analysis using the same numerical simulation model in order to estimate the initial oil production of the Fishbone well with different branch lengths (from 100 to 450m). The results from case#1 are presented in Figure 2, which shows that the initial daily production grows with the increase of the branch length. The optimum length of a single branch was 300m, and be the production did not show a significant improvement beyond this length. Another sensitivity analysis study was conducted by Xing, et al. [34] on case#2. As a result, the optimal branch length in the ultra-thin reservoir was 200 meters. Apparently, the optimum length of the branches is related to the petrophysical proprieties and the thickness of the reservoir. When the branch goes further, it may reach the reservoir formation top with low reservoir petrophysical proprieties. Above a specific limit, the productivity is the same or slightly different. The aim is to maximize the reservoir contact with less drilling cost.

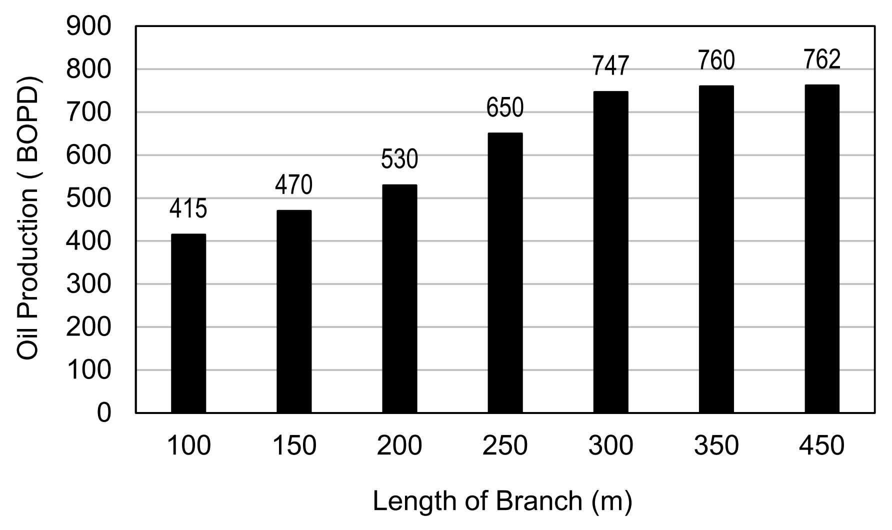

Figure 2: Effect of the length of the branch on production [39].

Sun et al. [40] used analytical methods to assess the Fishbone production in a case study (case#3) where the total length of the main borehole and the branches for the different designs was 800m, and the angle between the branch and the main borehole was 45 degrees (see Figure 3). From the results of Figure 4, it is seen that the Fishbone geometry with two different branches of 100m and 300m yielded the maximum production rate. They also mentioned that the longer branch is preferred to be positioned as the first one in the series of branches as it will ensure the maximum contact from the very beginning part of the reservoir, and the long one will be extended along all the reservoir [40].

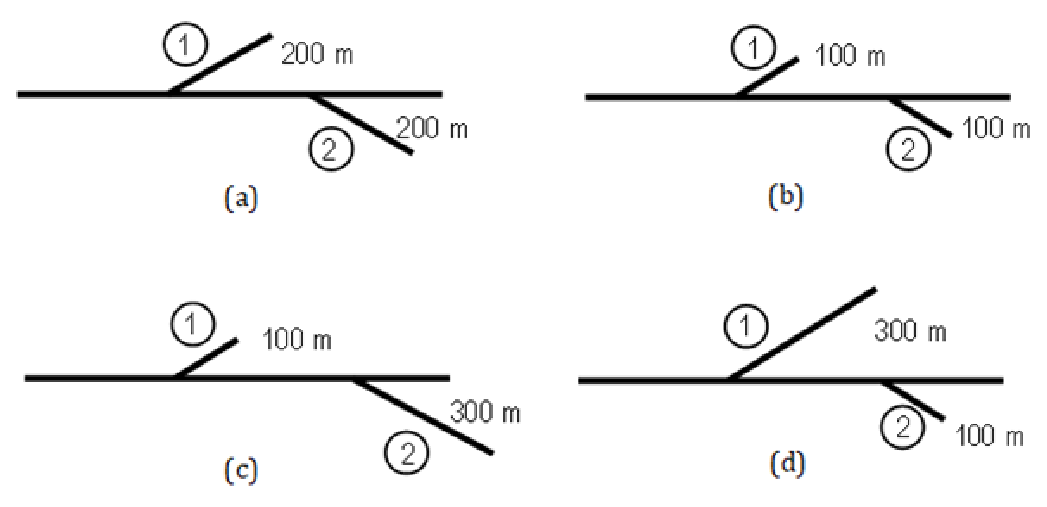

Figure 3: Schematic diagrams of Fishbone wells geometries with different branches length [40].

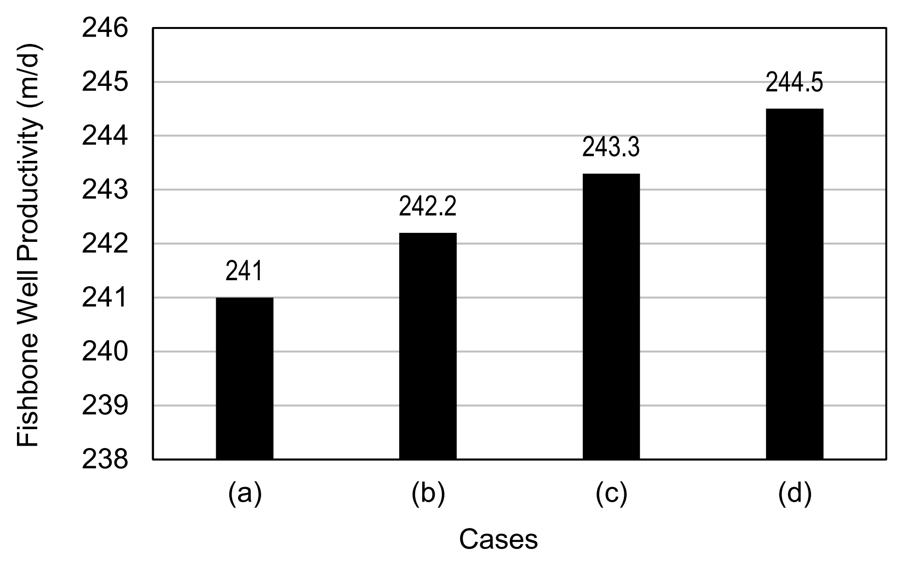

Figure 4: Productivity of Fishbone wells with different lengths of the branches [40].

Branch Angles

Manshad, et al. [39] simulated four branches of Fishbone design numerically with different angles from the main horizontal bore hole. The results of Figure 5 show that the optimum production rate of case#1 corresponds to the branche's angle between 20˚ and 30˚. The second study (case#2) presented by Xing, et al. [34] investigated the productivity of four Fishbone geometries with different angles between the branches and the main well as follows: (a) the angle between the branches and the main lateral is 15˚, b) the angle between the branches and the main lateral is 20˚, c) the angle between the branches and the main lateral is 30˚, d) the angle between the branches and the main lateral is 45˚. The comparison between the oil production rates for these different geometries (a, b, c, and d) confirmed the same outcome as case#1, implying no significant production improvement below 30˚ angle for the branches. The results of the analytical models' calculations developed by Sun, et al. [40] depicted in Figure 7 showed that when the branching angles are equal, the Fishbone well has the lowest productivity, and it increases when the angle difference increases. In this case#3, the total angle was 135 degrees, the branching length was 200m each, and the main borehole length was 400m. The Fishbone geometries studied by Sun, et al. [40] are presented in Figure 6.

In conclusion, the control area of the Fishbone design increased with the increase of branch angle. It also changed the interference between the branch and the main horizontal well. The interference among different branch holes increased by increasing the angle to an optimum point.

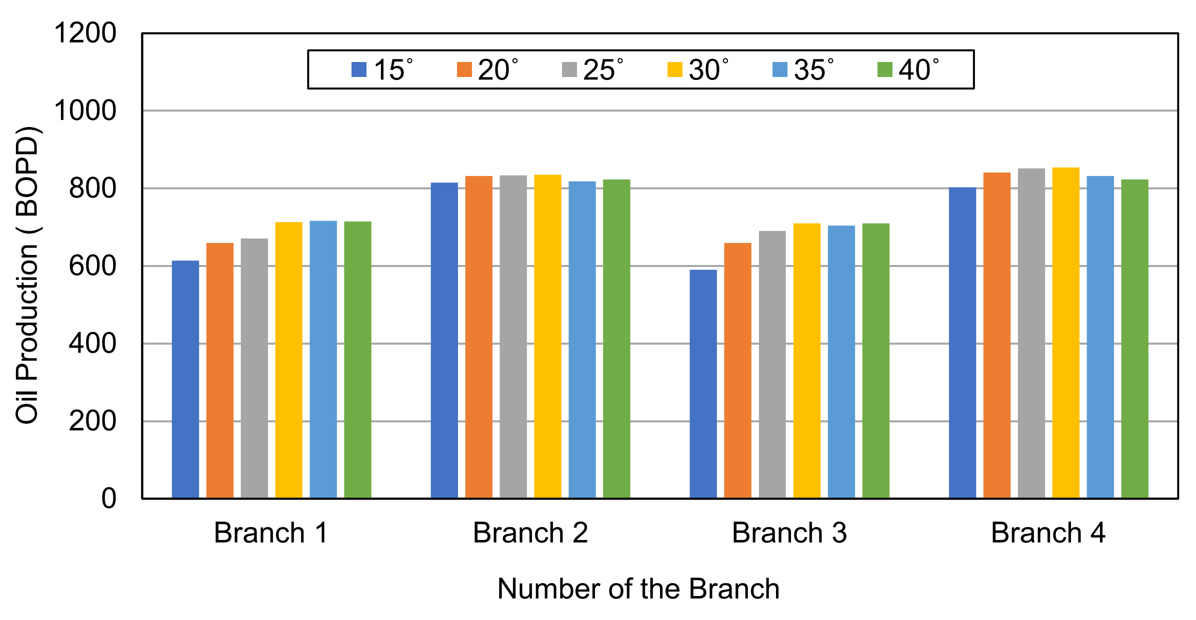

Figure 5: The effect of branche's angle on Fishbone daily production rate [39].

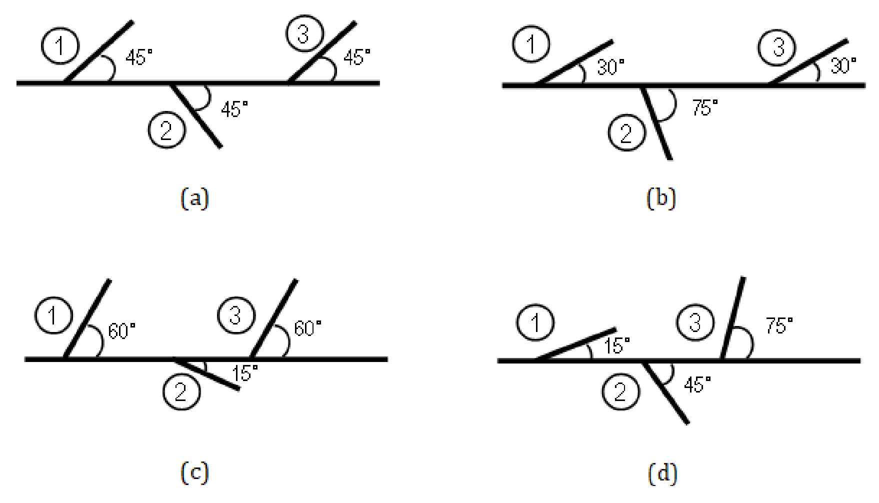

Figure 6: Schematic diagrams of four Fishbone wells geometries with different branche's angles [40].

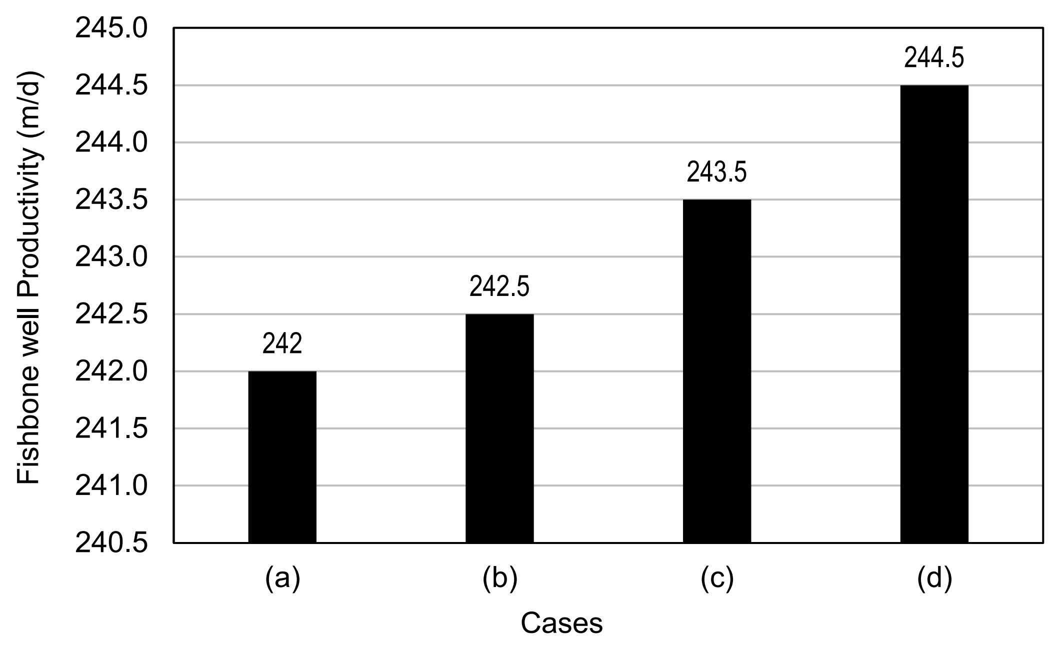

Figure 7: The productivity of Fishbone wells with different branche's angles [40].

Distance Between Adjacent Branches

Many factors need to be considered for branches Kickoff Point (KOP) selection, such as geological properties, the formation's thickness, and the build-up radius (related to the drilling program and well deviation tools). It requires a good understanding of the effect of the branches' intersection, thus, enough distance to ensure a wide drainage area. Xing, et al. [34] recommended 80m to 150m as an appropriate range of space distance between two adjacent branches.

Four branching geometries with 200m lengths each and the main borehole of 400m long with an angle of 45 degrees are presented in Figure 8. Sun, et al. [40] applied analytical models to study the effect of the distance between branches on the rates of daily well production from developed analytical models [40]. The results showed that the productivity was higher when the branches were placed closer to each other (see Figure 9). Sun, et al. [40] stated that the interference between branches decreases and the distance increase.

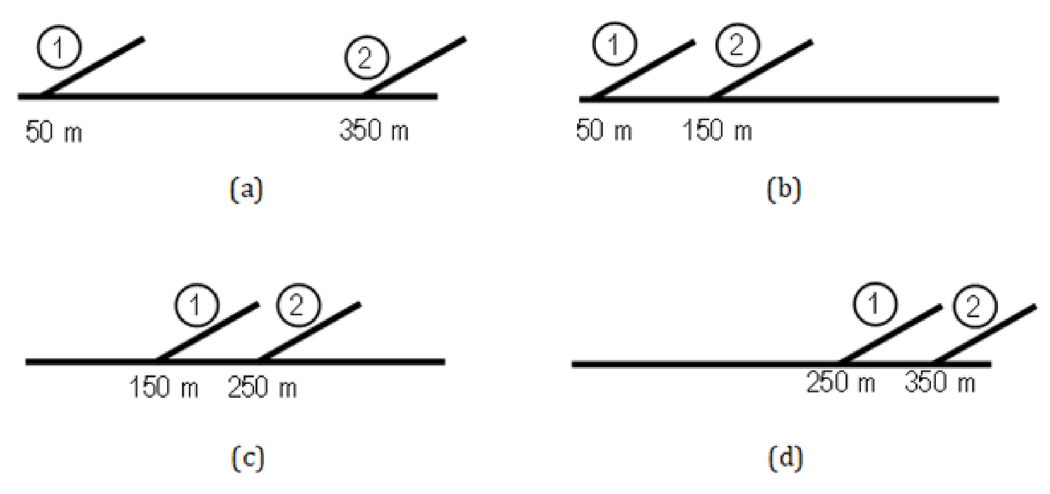

Figure 8: Schematic diagrams of Fishbone wells with different branches locations and spacing [40].

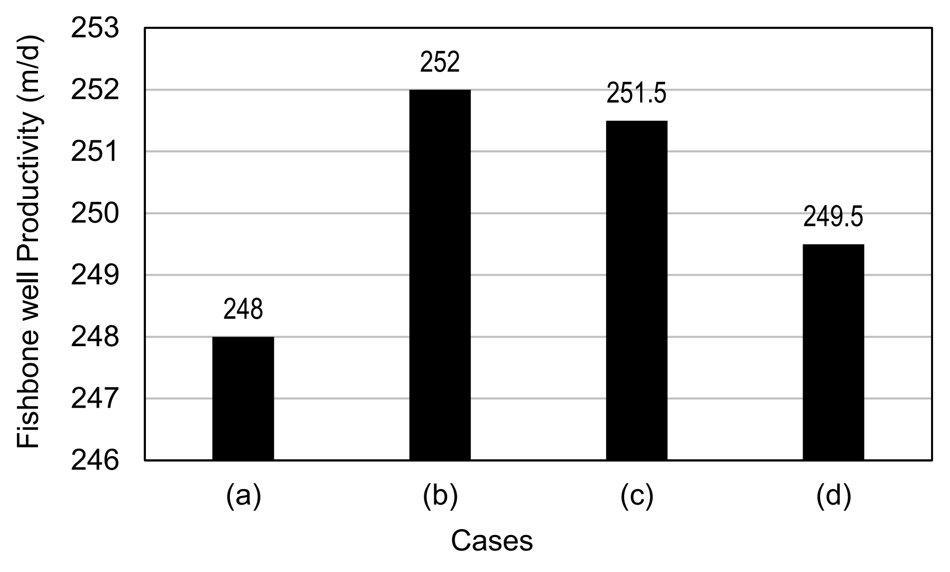

Figure 9: Fishbone well productivity with different branches locations and spacing [40].

Fishbone Well Design Optimization

In this section, a summary of two different approaches that have been used for well design optimization of Fishbones is presented. This includes the analytical models and data-driven models.

Analytical Models

Predicting the oil and gas production rate from a reservoir is measured by reservoir deliverability. The bottom hole pressure significantly affects the production rate, depending on the completion type and the artificial lift methods.

Four of the main deliverability models that are used in the industry are classified based on the well completion type and include the vertical well, main lateral well, hydraulic fracturing, and multi-branch lateral well (including Fishbone well).

Guo, et al. [41] reported some of the existing analytical models for reservoir deliverability. These models consider the flow regimes to study the relationship between the production rate and the bottom hole pressure. The models mainly depend on the reservoir pressure, boundary type, distance between branches, permeability (vertical and horizontal relative permeability), wellbore radius, near-wellbore effect, pay zone thickness, and the reservoir fluid proprieties. The relation between the above parameters is called the Inflow Performance Relationship (IPR).

For a Fishbone well, Guo, et al. [41] suggested the following equation for oil wells to predict the production rate:

$$q_g = \sum_{i=1}^{n} \frac{7.08*10^{-3} k_H L_i \left(p_{pl} - p_{wf}\right)}{\mu_o B_o \left\{ I_{ani} \ln\left[\frac{h I_{ani}}{r_{w_i}\left(I_{ani}+1\right)}\right] + \frac{\pi y_{b_i}}{h} - I_{ani}\left(1.224 - s_i\right)\right\}} \quad (1)$$

For the gas well, the equation is presented as follows:

$$q_g = \sum_{i=1}^{n} \frac{k_H L_i \left(p_{pl}^{2} - p_{wf}^{2}\right)}{1424 \overline{\mu_g} z T \left\{ I_{ani} \ln\left[\frac{h I_{ani}}{r_{w_i}\left(I_{ani}+1\right)}\right] + \frac{\pi y_{b_i}}{h} - I_{ani}\left(1.224 - \left(s_i + D q_g\right)\right)\right\}} \quad (2)$$

The above flow equations consist of two parts. One corresponds to the drilled region where the flow between the branches is assumed to be pseudo-steady-state and pseudo-linear flow, the second region contains the formation matrix, and the flow, in this case, is supposed to be pseudo-steady-state radial flow.

Equations (1) and (2) can be presented in the following general forms:

For oil reservoirs:

$$q = \frac{\left(p - p_{wf}\right)}{\frac{1}{J_{PL}} + \frac{1}{J_R}} \quad (3)$$

Where J_{PL} and J_R are as follows:

$$J_{PL}=\frac{7.08\times10^{-3}k_HL_i}{\overline{\mu_o}B_o\left\{I_{ani}\ln\left[\frac{hI_{ani}}{r_{w_i}\left(I_{ani}+1\right)}\right]+\frac{\pi y_{b_i}}{h}-I_{ani}\left(1.224-s_i\right)\right\}} \qquad (4)$$

$$J_R=\frac{k_Hh}{1424\overline{\mu_o}B_o\left(\frac{1}{2}\ln\left[\frac{4A}{\left(\gamma C_A r_{PL}^2\right)}\right]\right)} \qquad (5)$$

For gas reservoir:

$$q=\frac{\left(p^2-p_{wf}{}^2\right)}{\frac{1}{J_{PL}}+\frac{1}{J_R}} \qquad (6)$$

Where J_{PL} and J_R are as follows:

$$J_{PL}=\frac{nk_HL_i}{1424\overline{\mu_g}\overline{z}T\left\{I_{ani}\ln\left[\frac{hI_{ani}}{r_{w_i}\left(I_{ani}+1\right)}\right]+\frac{\pi y_{b_i}}{h}-I_{ani}\left(1.224-\left(s_i+Dq_g\right)\right)\right\}} \qquad (7)$$

$$J_R=\frac{k_Hh}{1424\overline{\mu_g}\overline{z}T\left(\frac{1}{2}\ln\left[\frac{4A}{\left(\gamma C_A r_{PL}^2\right)}\right]\right)} \qquad (8)$$

In the above equations:
L_i: Length of the branch, ft
n: Number of the branches
r_{w_i} : Radius of the branch, ft
y_{b_i} : Distance between branches, ft
s_i: Skin Factor
μ_g : Gas viscosity, cp
μ_o : Oil viscosity, cp
Z: Gas compressibility factor
B_o: Formation volume factor, bbl/STB
T: Reservoir temperature (ºR)
h: Net pay thickness, ft
q: Gas flow rate at pressure p, (bbl/day).
D: Non-Darcy flow coefficient, d/Mscf
A: Reservoir drainage area (acre).
C: Stabilized performance coefficient (MMScf/D.psia^{2m} or MMScf/D.(psia^2/cp)^m)
m: Dimensionless deliverability exponent, defined as the line's inverse slope on a log-log plot of the change in pressure-squared or pseudo-pressure versus gas flow rate.
p_{pl}: The average pressure at the edge of the inner region.
γ : Fluid specific gravity, water = 1.0
I_{ani} : the relationship between the horizontal and vertical permeability, which is presented as:

$$I_{ani}=\sqrt{\frac{k_H}{k_V}} \qquad (9)$$

where:

k_H: Horizontal permeability, mDarcy
k_v: Vertical permeability, mDarcy
r_{pl}: The equivalent radius of the inner region can be calculated using the following equation:

$$r_{pl}=\sqrt{\frac{(n+1)2Ly_b}{\pi}} \qquad (10)$$

The inner region represents the drained volume and the outer region

Ahmed, et al. [42] proposed the following empirical IPR relationship:

$$\frac{q_o}{q_{o,max}}=1+a\left(\frac{P_{wf}}{P_{avg}}\right)^b n^c+d\left(\frac{k_H}{k_V}\right)^e\left(\frac{P_{wf}}{P_{avg}}\right)^f+gL \qquad (11)$$

Constants a to f in the above equation are as follows:

a = 1.056150135 b = 1.35 c = 0.12837 d = -2.49525
e = -0.02782 f = 1.7 g= 2.52E-06

The proposed IPR correlation considers the effect of permeability anisotropy, length, and the number of branches for a dry gas reservoir.

The model developed by Sun, et al. [40] predicted the pressure distribution, considering the pressure gradient threshold in the heavy oil reservoir. This analytical model is based on the non-darcy seepage law, which states that the oil flows when the pressure gradient overcomes the initial pressure. The derived pressure difference equation for the oil flow among the branches in the horizontal well is represented as Sun, et al. [40]:

$$\Delta p_{wt}=p_1-p_2=\frac{16\rho q_t^2}{\pi^2D^4}\left(1-\cos\theta\right)+\frac{32\rho Q_tq_t}{\pi^2D^4} \qquad (12)$$

Where Δp_{wt} is the variation of the pressure in the horizontal branch before and after passing the KOP of the branch from the lateral section. Q_t is the flow from the very endpoint of the main horizontal well and q_t is the flow of the end of the branch. θ is the angle between the branch and the main lateral, *D* is the diameter of the main wellbore, and the geometries of the branches are considered in this study equal and is as depicted in Figure 10.

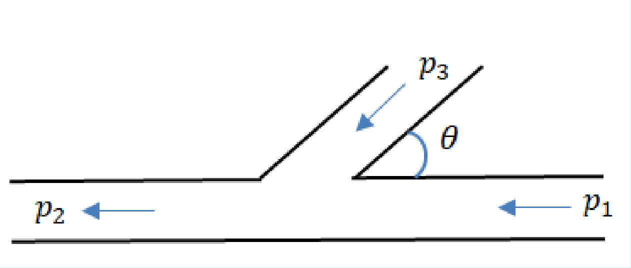

Figure 10: Fishbone flow configuration [40].

Data-driven Models

Data-driven models take into consideration the relationship between the input and the output of a system to find the existing correlations for future applications. These models do not rely on the physical sense of the problem compared to the physical-based models. Here, some of the data-driven models that have been used for the Fishbone well designs are presented.

Artificial Neural Network: In 1940, Artificial Intelligence (AI) techniques were introduced to the industry. Artificial Neural Networks (ANNs) are one of the practical AI tools applied in classification, prediction, and optimization operations [43]. It comprises neurons, hidden layers, inputs, and outputs data [44]. These data play the role of both training and testing to measure the reliability of the ANN model [45]. In the oil and gas industry, machine learning and optimization algorithms are utilized by various applications to address petroleum industry challenges [46-51].

Buhulaigah built an ANN model for oil production rates in multilateral wells. The statistical errors analysis, including average percentage relative error, average absolute percentage relative error, the standard deviation of the absolute errors, and coefficient of the correlation in comparison with the Borisov method, showed promising results compared to the analytical method [52].

Hassan, et al. [53] developed a mathematical equation using the optimized ANN model. The input data were the flowing bottom hole pressure (P_{wf}), permeability ratio (Kh/Kv), and length of each lateral. The output is the well production rate, as shown in Figure 11. The developed ANN model provided good accuracy with 98%. The absolute average percentage error was about 2.23%.

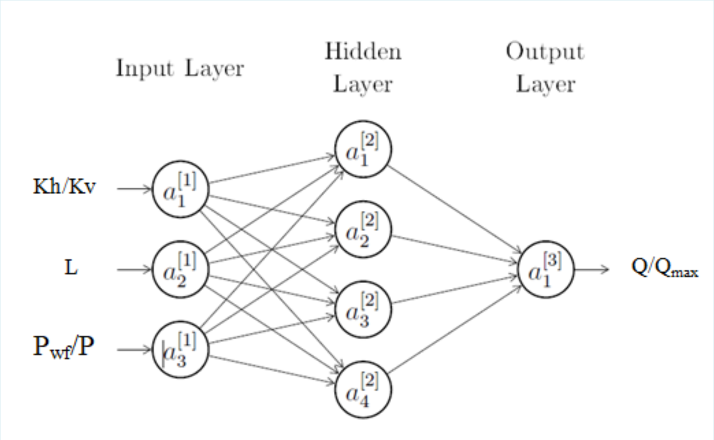

Figure 11: Artificial neural network model architecture with input, hidden, and output layers [53].

The optimized ANN used by Hassan [53] showed good accuracy. The average absolute error was 7.23%. A powerful productivity prediction correlation was extracted from the ANN model, which can predict the flow rate based on the weights (w) and biases (b) of the ANN model [53] as:

$$\frac{q}{q_{max}} = \sum_{i=1}^{N} w_{2i}\left(\frac{2}{1+e^{-2\left(w_{li,1}\left(\frac{K_h}{K_v}\right)_j + w_{li,2}L_j + w_{li,3}\left(\frac{P_{wf}}{P_{avg}}\right)_j + b_{li}\right)}}\right) + b_2 \qquad (13)$$

The correlation coefficient was 0.979, relatively higher than the previous case. The developed data-driven empirical correlation results were also compared with Vogal's correlation and the actual gas rate [53].

Adaptive Neuro-fuzzy Inference System: Another artificial intelligence method used for Fishbone productivity estimation is the Adaptive Neuro-Fuzzy Inference System (ANFIS). The objective is to maximize the correlation coefficient and minimize the estimation error. By raising the cluster radius, the results will be much better. Hassan, et al.

[53] used five membership functions, a cluster radius of 0.8, a linear output membership function, and 200 as an iteration number. The obtained results were 13.92% for Average Absolute Percent Error (AAPE) and 0.985 for R^2.

Radial Basis Function Network: Radial Basis Function (RBF) network was used to predict the production rate with different parameters values and number of neurons [54]. The results showed that the AAPE raised and the Coefficient of Determination (R^2) score decreased by increasing the goal of spread values of the RBF network. Above 20 neurons, the RBF network remains stable. The optimum model had 50 spread and 0.0 goal. Moreover, the obtained R^2 was 0.9851, and the AAPE was 11.14%, [53]. The most common problem in the Fishbone wells was finding the most accurate model for well productivity from the literature. The last results showed high accuracy results from the artificial intelligence models and that they can help the petroleum engineering industry investigate more on FbD efficiency and use those models as powerful predictions tools.

Underbalanced Drilling Technology

Fattah, et al. [55] reviewed different case studies from Middle Eastern oil and gas fields and worldwide on the underbalanced drilling techniques. Three example cases are summarized in Table 1.

Location	Onshore Belayim oil field Gulf of Suez area [55].	Western desert gas field area in the central part of the western desert block [55].	Iranian oil field [56]
Well target formation	The sandstone of zone III (Belayim formation, Feiran member).	Unit 3 of the Mesozoic Lower Safa reservoir.	Asmari formation.
Depth	2335m TVD, 2854m MD.	3-7/8in. · 500m horizontal section.	2938m MD (2567m TVD).
The objective	Increase rate of penetration, enhance well control, reduce the occurrence of lost time incidents, and increase well productivity.	Reservoir damage prevention.	Decreasing the drilling-induced formation damage, drilling fluid losses elimination, and drilling performance improvement.
Tools	UBDS and power-pack motor of 1.15˚BH c/w MWD Impulse, VPWD, ADN tools (inclination at the bit, annulus and string pressure, GR resistivity, density-neutron) with 2 · 3-1/2in. W.FORD float valve + motor restriction sub (nozzle 14/32 in.).	The technic of gasification was through drill pipe injection Use 5” DP, 5” HWDP, and 6.5” DC Without a downhole motor.	
Results	ROP enhancement from 4 m/h while sliding to 50m/h in the sand, and it was 8–10m/h in anhydrite compared to 2–4m/h in conventional overbalance drilling.	ROP was estimated to be between 5 and 10m/h Compared to 2–3m/h in overbalanced drilling.	Safe well drilling without any loss circulation, thanks to UBD technology, without Quality, health, safety, and environmental (QHSE) incidents After drilling five wells, $1.4MM has been saved.
Reservoir characteristics	Reservoir pressure : 3000– 3500psi (0.3917–0.4569psi/ft).	Micaceous sandstones with the permeability of (1–500md).	Fractured carbonated formation. Reservoir pressure was 2622psi & the temperature was and 141˚F. The reservoir permeability is 0.1–1000md, and the porosity was 9%.
Mud	Nitrified mud (500SCFM+ 230GPM diesel)	**Liquid phase:** crude oil with density 6.84ppg 41.7˚API. **gas-phase:** Nitrogen	The liquid phase, which is oil from the Gachsaran field which, has the same characteristics as the reservoir fluid The gas-phase was nitrogen.

Table 1: Three successful case studies of worldwide well drilling using underbalanced technology [55,56].

The use of coiled tubing technology offers a great benefit in drilling when it is integrated with the underbalanced drilling operation. In Indonesia, a highly depleted reservoir was targeted by a multilateral well using Underbalanced Coiled Tubing Drilling (CT-UBD). The drilling fluid was designed based on the geomechanical and petrophysical analysis and considerations of drilling-related problems such as wellbore stability, lost circulation and formation damage (clay swelling, fine migration, phase trapping). The decisions were severe due to the low wellbore pressure as a result of UBD. The wellbore diameter, water influx, and gas production parameters affect the pressure and injection rate calculations. It took into consideration the pore pressure, drawdown pressure, minimum velocity, and motor capacity. The coiled tubing diameter used for this case was 2 7/8" a 6" borehole and downhole motor with a maximum flow rate of 350gpm. The objective was to improve production by drilling the new zones with multilateral instead of hydraulic fracturing the depleted zone. Nitrogen was used as the drilling fluid to decrease the wellbore instability, vibration, erosion, and wellbore reservoir wall damage. The results showed an increase of 3.67 times in the well production rate [57].

Unconventional Plays

The "sweet spots" are the highly productive zone in unconventional reservoirs, mainly due to the existence of natural fractures [14]. The aim of drilling with underbalanced fluid in tight reservoirs is to eliminate the formation damage caused by the mud penetration into the formation, which is not the same as drilling into conventional reservoirs [58]. In Algeria, a very tight gas reservoir with less than one millidarcy permeability was drilled using UBD. The result was an increase in the gas flow rate, and consequently, the hydraulic fracturing operation was discarded [59]. The UBD technology identified the near-well permeability and flow units. Meanwhile, the rate of penetration increased compared to drilling in overbalanced conditions [60].

An increase in natural gas production from the Risha Gas field in Jordan was studied between 1989 and 2004. This enhancement was caused by underbalanced drilling of one well in Ordovician tight sandstone followed by three other wells re-entries to increase the stimulated reservoir from 2002-2005.

Maranuk, et al. [61] stated that among 111 active drilling rigs in the Marcellus shale in the Northeast United States, 27 rigs used underbalanced drilling, and 23 rigs used air drilling. The downhole assembly was composed of air hammers supporting severe shocks and vibrations during air drilling. Downhole mud motors with a self-lubrification system were to extend their life. Also, measurement while drilling (MWD) was used with more robust electronics and shock absorbers, and a tri-cone or Polycrystalline Diamond Cutter (PDC) bit was used. These tools made the operation economically viable with less non-productive time, less drilling fluid cost and reduced the cleaning process. The case study from Marcellus shale in Washington County in southwestern Pennsylvania showed a significant increase in ROP and drilling cost reduction using directional air drilling at about 2133.6m depth [61].

Fishbone Technology Field Studies

Field studies are the most liable approach to investigate the applicability of all the new engineering technics, and it is highly recommended to calibrate the simulation by the experimental test for each field application. Stalder, et al. [62] presented a successful Fishbone well drilled in Venezuela. Nine branches were drilled, with the length of each branch being about 900 meters. The aim was to increase the production of a high viscous oil by maximizing the reservoir contact for high fluid mobility. The lithology of the reservoir in the Zuata field was non-homogeneous sand with different barries and permeable discontinuities. The results showed an increase in the well production with an 18% increase in the drilling cost.

Manshad, et al. [39] studied the application of Fishbone design in the giant Middle Eastern oil field. The characteristics of the reservoir with the net pay thickness of 118m located at different depths of 2,709 to 2,850m consisted of crude oil of 19.95˚ API, 4.44–5.44cP viscosity, and the Gas-to-Oil Ratio (GOR) was between 276 and 441 Standard Cubic Foot per Stock Tank Barrel (SCF/ STB).

The goal was to reach 250 thousand Barrels of Oil Per Day (BOPD) based on the company's initial oil field development plan. This achievement was considered as the highest production plateau in that field. The purpose of drilling a Fishbone well was introduced for environmental reasons, which made hydraulic fracking very challenging because it required surface facilities near a residential area. The second reason was to prevent any kind of surface pollution with a minimal network pipeline and underground water pollution. The third reason was to increase the recovery factor, which was about 19%, relatively low compared to other case studies [39]. Drilling the horizontal well section took 99 days with a mud weight between 1.22 and 1.25gm/cm^3, and the KOP was 2974m.

Fishbone well path design in the Middle East resulted in a production increase of about 393%. In the meanwhile, the drilling cost increased by 130% compared to a horizontal well. The optimum Fishbone well characteristics were four branches with a length of 300m each and a 30˚ deviation from the main horizontal well.

Bazitov, et al. [63] presented the first application of FbD at Vankorskoe Field, Russia. The operator adopted the FbD strategy to improve the single-well productivity from the very thin formation named Nizhnekhet 1. The primary purpose of using Fishbone well design was to drill a multilateral well with nine additional branches 1m above and below the main horizontal wellbore trajectory. This operation offered a two-times increase in productivity compared to the conventional horizontal well [63]. The success of the first operation opened the opportunity for Fishbone applications in many complex geological formations from different regions in Russia.

Another successful Fishbone case is drilling in a tight carbonate formation at the Abu Dhabi National Oil Company (ADNOC) onshore field. The aim was to connect the natural fractures within the reservoir to increase the permeability and productivity by drilling 40 Fishbone sub. Each sub had four branches, each 12m long; the angle between the branch and the main borehole was 90 degrees. The productivity increased by 2.5 times compared to nearby wells in the same field [64].

Torvund, et al. [65] presented a recent completion of one of the lateral legs of a dual-lateral subsea well in the Aasgard Field (Norway) with multilateral drilling simulation technology in one of the lateral legs. They created 144 new branches into an oil-bearing tight sandstone formation named Lower Garn [65]. The rate of production increased by 20% compared to the near horizontal wells. In Vostochno-Messoyakskoye onshore field in Russia, 14 sidetracks were drilled in a sandstone formation with multilateral wells using the Fishbone technology with a total of 10km of horizontal section. The results showed an increase of 40% in oil production rate compared to the conventional horizontal wells. In the East Messoyakha field, drilling eight horizontal Fishbone sidetracks in a low permeable formation showed an increase of 164% in production rate compared to the horizontal well. The rate of production was similar to producing from a hydraulic fractured reservoir. The total horizontal drilling length was 5,154m [66]. The Productivity enhancement in the United Arab Emirates (UAE) showed an increase of 300% during the application of Fishbone well technology in a very tight reservoir. The application of hydraulic fracturing caused many problems to stimulate the reservoir in the UAE. The Fishbone technology connected the natural fractures of the reservoir with a valid extension and drilling trajectory orientation. In this case, the Fishbone design had a total of 1,951m in length with 40 subs, and each one had four branches with each 12m long [67].

Lezin, et al. [68] presented a case study from the Vankor oilfield, Krasnoyarsk area in Eastern Siberia. They used an adaptable-biopolymer drilling fluid system to drill multilateral wells successfully. This adaptable fluid had many advantages as an inhibitor. It increased wellbore cleaning performance and fluid filtrate reduction in the reservoir wellbore. The laboratory experiments, including the erosion test, swelling tendency, plugging permeability test, and filtration cake, proved the efficiency of drilling thirty-seven horizontal Fishbone branches with the biopolymer fluid. The results showed a recovery increase of about 30% compared to conventional horizontal drilling, and the production rate increased by about 50%. The chemistry of the materials used for this drilling fluid was: sized marble 5 microns, sized marble 50 microns (filter cake bridging agent), caustic soda (filter cake bridging agent), biocide, drilling starch (filtration reduction agent), biopolymer (viscosities), polyglycol (clay inhibitor), potassium chloride (clay inhibitor), lubricant (Friction factor decreasing agent). Lezin mentioned that this technology allows sidetracking without any additional equipment. The maximum inclination angle was 101 degrees.

Rylance, et al. [69] stated the application of Fishbone technology in the Srednebotuobinskoye oil and gas condensate field in Eastern Siberia. The reservoir formation is a porous sandstone reservoir with a horizontal permeability of 350mD, 140atm, and 14°C initial pressure and temperature, respectively.

The first Fishbone stimulation method applied in an onshore oil field in the United Arab Emirates was in a zone with many limitations for hydraulic fracturing. The objective was to connect natural fractures in a reservoir with poor vertical permeability than horizontal ones. An acid injection with 15% HCl was used in 40 branches; each one has from 40 to 160 feet in length, which dissolved the carbon formation and increased permeability. The productivity was enhanced three times, which proved the successful application of Fishbone stimulation in UAE fields [70].

One of the challenges in Kita-Akita oil field redevelopment in northern Japan was the necessity of a severe height control of the hydraulic fracturing, and this is affected by the horizontal stress variation, which changes the fracture geometry. The results were justified by the 1D and 3D mechanical earth model (MEM) constructed. The problem with stress magnitude and direction variation caused by the active tectonic history with a high folding and faulting increased the heterogeneity within the formation with a high mechanical proprieties variation.

The drilling Bottom Hole Ammebly (BHA) consists of a Positive Displacement Motor (PDM) with a bend-sub, and a PDC bit of 123.8mm diameter was used to drill the lateral branches from the main horizontal wellbore in the case study of the Vankor field in 2014. The branches had a small diameter compared to the main borehole, with a 152.4mm diameter drilled by Rotary Steerable System (RSS) to prevent entering the liner into branches and prevent the liner stuck [63].

Voronin, et al. [71] presented a BHA with RSS, and Logging While Drilling (LWD) tools used at the Vostochno-Messoyakhskoye field. The RSS comprises a bit, near-bit stabilizer, non-rotating module, RSS Controller, and inclinometer module with stabilizer.

The Fishbone well drilling of eight sidetracks in the East Messoyakha field was implemented by a Derrick Drilling Machine (DDM) in six horizontal holes and point-the-bit RSS in the other two horizontals. The results showed that the DDM is more effective in reducing the kickoff operation time. This is caused by the offset mechanism and the design features. 7.5 hours is the time spent by the RSS to kickoff. On the other hand, the average kickoff time with DDM was 4.9h, which confirmed that the DDM is more cost-effective than the RSS, so it is highly recommended for FbD as we are expecting many kickoff operations [66].

Geosteering technology was applied to drill Fishbone well in “hard to recover” reserves in the Russkoye field. It is considered one of the largest fields in Russia. The kickoff operation was implemented using RSS and the LWD tools data to select the suitable location of the kickoff points. The result showed that 98.9% of the drilled hole was through the Pokur suite formation’s geological target. The production rate increased by 20% to 60% compared to the conventional horizontal wells. The Fishbone well had a high performance compared to the other wells, and the production rate increased by 50% compared to the other wells [72].

To prevent the high risk of collision between the Fishbone branches and to ensure the best trajectory planning, a well placement workflow was applied in the Russkoe field in Russia. The distance between the micro-borehole was relatively small, between 30m and 40m. This method included real-time data interpretation for the trajectory regulation in addition to the experienced drilling engineering team [73]. The BHA tool was composed of RSS for directional drilling, MWD, for real-time wellbore positioning and data transmission using the telemetry method. The essential data transmitted up the drill pipe by MWD were the inclination and the azimuth. In addition to that, the BHA had a density-neutron LWD tool to deliver the formation densities. The Multilayer bed boundary detection technology was also included in the BHA, which provided conventional resistivity measurements and gamma-ray detection. This modern design was successfully applied for FbD in a very complex geological environment with difficult drilling conditions [73]. Table 2 shows the existing patents in Fishbone well configurations.

Inventors	Date of Patent	Title	Description	Source
Wang Xiang Zhou Weidong Zhang Hui Li Luopeng Chen Xiaohua Wang Zhihong Li Dalei Li Wei	October 22nd, 2021	Drill pipe recovery device and drilling device of Fishbone well	This patent is for drill pipe invention of Fishbone well drilling. Composed of a shell and a central pipe to make sliding easier.	[74]
Gao Yonghai Chen Ye Sun Baojiang Zhao Xinxin Li Chen Litao	April 06th, 2021	Fishbone-shaped well structure and method for exploiting natural gas hydrate	This patent is to disclose the application of Fishbone well in natural gas hydrate exploration to inject the CO2 to crack the hydrate layers and produce from them.	[75]
John L. StalderSon V. PHAM	October 8th, 2019	Fishbone well configuration for SAGD	Fishbone geometry is compelling for Steam-Assisted Gravity Drainage (steam-based oil recovery).	[76]
John A. STANECKI Thomas J. Wheeler.	August 20th, 2019.	Oil recovery with Fishbone wells and steam	This patent described an effective Fishbone well design for steam-driven based oil recovery methods	[77]
Sergei A. FILATYEV Pradeep Ananth Govind Thomas J. Wheeler	August 6th, 2019	Thermal conditioning of Fishbone well configurations	Fishbone technology is an effective well configuration for Steam-Assisted Gravity Drainage, which can overcome many challenges concerning resistive heating.	[78]

Bo Chen Qing Chen Thomas J. Wheeler	May 14th, 2019	Non-condensable gas coinjection with Fishbone lateral wells	This patent demonstrates the injection of steam and then the Non-condensable gas coinjection with two or more Fishbone lateral wells.	[79]
Liu Qingyou Zhu Haiyan Tao Lei	April 22nd, 2015	Drilling and completion and production increasing method for shale gas reservoir of multilateral Fishbone horizontal well	The patent discloses the productivity-increasing due to FbD in shale gas reservoirs. This technology has been proven to be cost-effective, with fewer pollution risks.	[80]
John L. Stalder Kevin A. Wilfing	November 27th, 2014	Radial Fishbone SADG	This patent suggests a radial pattern for steam-based oil recovery methods using Fishbone well configuration.	[81]
Wayne R. Dreher Partha Sarathi	June 25th, 2013.	A Fishbone well configuration for in situ combustion	This patent defined the application of Fishbone for injection purposes. The aim is to increase the recovery by the in situ combustion method.	[23]
Bu Zhenshan Wang Pingping Yu Jiyou Ma Haiyu Lihong Zhou Yongping	September 09th, 2011	Drilling type well completion technology for Fishbone branch borehole	This patent explains the way how to create the Fishbone well. To prevent the collapse of the micro-holes, they suggested a glass fiber to the reinforced plastic casing.	[82]
Xu Ping, Zhang Fangli Xu Ning Liu Qicheng in Tianzhong Junsheng	March 16th, 2011	Fishbone well-type structure	Fishbone well type structure with the specific configuration: Number of branches: 2 to 6. Length of each branch: 150 to 400m which can be different or the same from one branch to another. The angle between the branch and the main lateral is between 10 to 50 degrees. The aim is to solve the fast production decrease from oil wells.	[83]

Table 2: Existing Patents for Fishbone Well Configuration.

Fishbone Drilling versus Hydraulic Fracturing

The unconventional hydrocarbon resources definition, according to the U.S. Environmental Protection Agency (USEPA), is “those whose extraction has become economical only with the advances that have occurred in modern hydraulic fracturing (often coupled with directional drilling) in recent years.” [84-85].

The unconventional reservoirs have very complicated characteristics in different locations worldwide and sometimes in the same lithology. To overcome these obstacles, many research and development projects have been launched recently, not for discoveries, but for an optimized way to increase the recovery considering the technical and the economic factors. Introducing hydraulic fracturing had a tremendous advantage on unconventional reservoir stimulation but with significant environmental dangers such as a large amount of water consumption during the hydraulic fracturing operation and the fluid leakage that could contaminate the groundwater and aquifers.

There are many limitations with multi-stage hydraulic fracturing in unconventional reservoirs, which were applied in the low permeability formations in the last 15 years. These problems include the fracture closure with proppant embedment or crushing due to depletion and increasing effective stress by decreasing the pore pressure. This poroelasticity effect will cause a rapid decrease in well productivity. The second challenge that was not well studied is the lack of knowledge about fracture propagation and the uncertainty of the formation stresses and the orientation changes after depletion [86]. The third challenge is the proppant displacement and the fact that the fracture is produced effectively from the open part of the propped fracture. The rate transient analysis results demonstrate that the production is limited to the propped zone of the fractures. In fact, a large amount of fluid injected to propagate the fracture is not necessary in this case if the proppant placement is well studied [87]. Fracturing fluid is also not equally distributed, which is affected by the injection rate, the size and the number of the perforations, as well as the distance between them. The results were proved using the FiberOptic as a frac diagnostics, negatively influencing the proppant distribution [88].

Even though many papers about treatment design optimization have been authored in recent years, fracture initiation is still a challenge that leads to fracture tortuosity and may cause screen-out. It can also cause the intra-well connection between the well stages leading to uncontrollable fluid distribution between stages [89]. These challenges can be overcome using Fishbone well design using different branches with about 2 inches diameter in different directions to intersect natural fractures and maximize reservoir contact. The results could be compared with hydraulic fracturing in terms of productivity index. FbD technology will open new insights and save substantial time and cost associated with drilling and completion. This method will ensure that the drilling will reach the most reservoir layers with just one well.

Fishbone technology is still at the very early stage of exploration and development. A comparison between the multi-stage hydraulically fractured reservoir and Fishbone well need to be made to prove the difference between these technologies based on the long-term productivity and the economic factor. To make this study consistent, the comparison should be based on an equal number of branches compared to the fractures stages. The length of each branch needs to be equal to the fracture half-length, with the same spacing and in the same reservoir location. Then, the sensitivity analysis will be based on the number of Fishbone branches compared to the number of fractures.

Studying the optimum design of a Fishbone, including the number, length of the branches, the distance between branches, and the angle between the main lateral and the branch, will affect the drilling costs, which depends mainly on the technical difficulties and the time the driller spends during the FbD operation.

Some challenges need to be investigated to study the FbD feasibility, and each one affects the successful drilling operation, including the following:

- The productivity quantification of the Fishbone well design depends on the well trajectory parameters described previously, the reservoir characteristics, and the drilling fluid. This complex study should be investigated using some numerical simulation coupled with IPR and Vertical Lift Performance (VLP) models.
- Estimating the Fishbone production performance is so challenging because of the complicated design and sometimes with more than one fluid phase flow.
- The branches' wellbore stability, the reservoir depletion effect, and the stresses magnitude and orientation changes on the microbore holes stability. This study needs integrated geomechanical and reservoir modeling.
- The interference between the branches causes the cross-flow in production. Analytical or numerical studies of the distance between branches as the main parameter could optimize the interference effect on the well production rate.
- Study of the effect of the drilling fluid, BHA selection, and the drilling operation method could prevent the wellbore damage and enhance the well cleaning challenges during underbalanced coiled tubing drilling of the Fishbone microbore holes.
- The effect of micro-branch intersection with natural fractures, the optimum intersection angle for fracture opening, and wellbore stability studies are other required studies in this area.
- Developing new technologies for Fishbone geosteering and micro-hole branches monitoring and geometry detection is required. Fishbone well placement is critical because a wrong operation leads to connections with zones of undesirable fluids as well as the challenges in drilling throughout natural fractures [90].
- FbD can be considered a booster for hydraulic fracturing operations to enhance production further. This may be a preferred alternative at this stage until more research work is done and the industry gains more knowledge about the FbD operation to determine the feasibility of replacing the FbD with hydraulic fracturing.

Other Potential Applications of Fishbone Drilling

The applications of the FbD technology can be further investigated in different domains. For example, it may overcome the challenges associated with geothermal developments, such as high reservoir temperature, abrasive and complex formations, fractured rock, and corrosive formation fluids, by maximizing the reservoir contact for better heat exchange and more steam generation. This will increase the potential of the geothermal well. Geothermal reservoir formation is brittle, demonstrating the ability to create microcracks using shockwaves after drilling a

Fishbone well. It will also minimize the drilling cost by drilling efficiently with one vertical and horizontal well and different branches to reach the target with less operational time. In this case, a new downhole design needs to be investigated, which may support the reservoir conditions in the geothermal well [91].

FbD technology can apply to enhance recovery during injection of CO_2 [92]. These reservoirs with very low permeability and porosity affect the displacement of the injected fluid to increase the reservoir pressure after depletion. Using Fishbone design, new research areas need to be developed for Carbon Dioxide-based Water Alternating Gas (CO_2 -WAG) injection. This will ensure better fluid mobility due to the high viscosity and enhanced recovery from tight formations. An example of that is the Bakken petroleum system, the primary recovery reaches 3% to 5%, which is economically not feasible, after injection of CO_2, the recovery was enhanced to 43% to 58%, which is still half of the existed reserves in place [93]. The application of the Fishbone wells during CO_2 injection needs to be further investigated, both technically and economically. It can be used as well for intermittent gas lift for hydrate mitigation and flare reduction [94].

FbD may also be used in Steam Assisted Gravity Drainage (SAGD) technology as a new method to extract heavy oil by supporting the gravity drainage by using the injected steam heat just near the horizontal well. This technique has shown a higher recovery amount which can overcome 60% of the total oil in place [95,96]. An innovative Fishbone infill well pair was developed for the first time in the Canadian oil sands play [91]. The Fishbone well was drilled successfully in the McMurray oil sand formation, with an important challenge of the collapse risk in the sidetrack junction points.

FbD technology will significantly affect the coalbed methane production, especially for coal beds with low permeability and compressive strength. Creating these micro-branches will have a positive effect due to the low performance of conventional stimulation by fracturing in vertical wells. An existing study by Ren, et al. [97] investigated the effect of FbD on the Liulin block of the Ordos basin in central North China. The gas production results were compared with the one from hydraulic fracturing. An intensive decrease in gas production of the fractured well in a short period after the production initiation; in the meantime, the products remained stable for three years using Fishbone well. The same causes mentioned above justify the rapid decrease, including the fracture closure and the proppant embedment, which were not ideally displaced within the fracture. The wellbore opening ensures stable production from the Fishbone well, with the same surface contact during the well life cycle. Since coalbed methane is mainly generated in a soft formation, the possibility of the proppant embedment is very high compared to the brittle formation. It is highly recommended to investigate the Fishbone design in coalbed methane from different regions around the world. It is expected that the drilling cost will be higher than hydraulic fracturing, but this will be compensated by the more cumulative production rate.

The coalbed methane is a naturally fractured reservoir (NFR) with different length scales [98,99]. This increases the possibility that the network will be open during drilling of micro-boreholes. This connection will complicate the production estimation [100]. The permeability in coalbed methane is very low; drilling Fishbone branches successfully in tight oil and gas formation can be projected to the coalbed methane application and vice versa.

Unconventional resources show a rapid production decline, which needs to be re-stimulated due to the fracture damage and conductivity decrease. The alternative solution for that was refracturing. At the same time, the depleted reservoir may cause in-situ stress changes due to the decrease of the effective stresses and casing collapse, which may change the perforation positions [101]. This makes geometry modeling, fracture propagation, and orientation prediction more complicated. Fishbone well technology can be applied in these areas as an alternative for refracturing operations in depleted reservoirs by intersecting the existing fractures, reaching new zones with lower costs, and using environmentally friendly technology.

Conclusions

- The case studies in the field demonstrate the successful implementation of FbD technology in various regions around the world and offer potential for further applications, boosting output from previously uneconomical reserves and promoting growth.
- The use of FbD technology and a deeper understanding of unconventional reservoirs will hasten the process of oil and gas extraction, enabling better production management in depleted reservoirs.
- A crucial aspect of FbD development is well-designed geometry, which contributes to improved drilling and completion in complex formations, particularly naturally fractured reservoirs.
- FbD enhances sweep efficiency by maximizing the coverage of Fishbone branches.
- The adoption of FbD will reduce drilling costs while minimizing environmental risks and enhancing reservoir recovery. Ongoing research and development in this area will help overcome current challenges and facilitate the creation of new, environmentally friendly stimulation methods.

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