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Review

A Comprehensive Review of Fishbone Well Applications in Conventional and Renewable Energy Systems in the Path towards Net Zero

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Abstract: Fishbone drilling (FbD) involves drilling multiple micro-holes branching out in various directions from the primary vertical or deviated wellbore. FbD is similar to multilateral micro-hole drilling and can be employed to boost hydrocarbon production in naturally fractured formations or during refracturing operations by connecting existing natural fractures. Key design elements in fishbones include determining the number, length, and spacing between the branches, and the angle at which the branches deviate from the main borehole. Fishbone wells have emerged as a promising technology for improving well performance and reducing environmental impact. In this paper, we present a comprehensive review of the different applications of fishbone wells in conventional and renewable energy systems. We discuss the potential of fishbone wells for enhanced oil and gas recovery, as well as their application in unconventional resources such as coal bed methane. Moreover, we examine the feasibility of fishbone wells in renewable energy systems, such as geothermal energy and carbon capture, utilization, and storage (CCUS). We highlight the various benefits of fishbone wells, including reduced carbon footprint, enhanced efficiency, and increased sustainability. Finally, we discuss the challenges and limitations associated with fishbone wells in different energy systems. This review provides a comprehensive overview of the potential and challenges of fishbone wells in reducing carbon footprint and improving well performance in a wide range of energy systems.

Keywords: fishbone drilling; oil and gas; geothermal; underground storage; carbon footprint

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1. Introduction

Multilateral wells represent a significant advancement in drilling techniques, allowing for multiple branches or offshoots from a primary well to more efficiently tap into various sections of a reservoir. One of the prominent techniques, horizontal multilateral drilling, has become increasingly popular in the exploration of unconventional reservoirs [1]. The design of these wells is determined by numerous factors, such as the geological, petrophysical, and geomechanical properties of the reservoir. The primary goal of multilateral drilling is to increase the wellbore's exposure to the formation, thus enhancing reservoir productivity and tapping into larger production zones [2].

Fishbone drilling (FbD), another drilling technique, is distinguished by micro-holes branching from the primary horizontal well, giving an appearance reminiscent of a fish's skeleton [3]. These micro-boreholes operate similarly to multilateral wells. Aspects such as the number, length, and angle of inclination of the micro-boreholes, as well as the spacing between their kickoff points, are crucial, as shown in Figure 1. Unlike conventional multilateral wells which originate from a primary vertical borehole, fishbone wells extend from multilateral wells connected to the well's lateral portion [4].

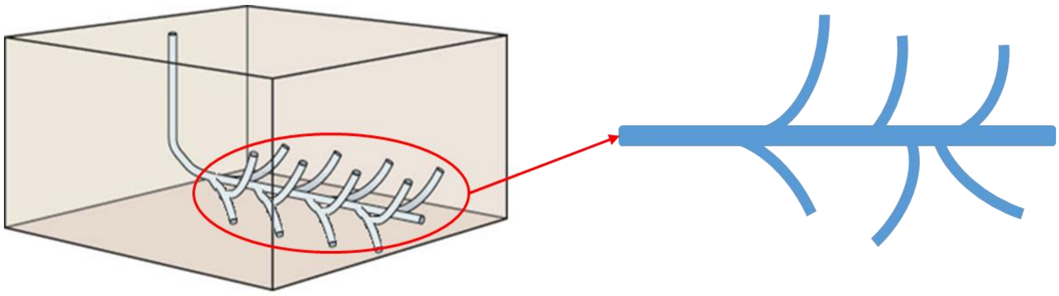


Figure 1. Fishbone drilling technology [5].

Drilling in fractured zones, especially in unconventional reservoirs with high natural fracture densities (known as sweet spots), can enhance production. However, this also comes with drilling-related challenges [6]. The main goal in these areas is to link up with existing fractures to improve flow rates by increasing permeability and establishing more fracture connections [7].

Recently, fishbone wells have emerged as an innovative approach in the domain of multilateral horizontal well technologies. They present unique economic and technical benefits [8]. Distinct from regular multilateral wells, fishbone wells consistently drill within a specified reservoir pay zone, making them beneficial across various reservoir layers [9]. Addressing a range of economic, environmental, and regulatory issues, fishbone technology serves as an ideal solution [10]. The central aim of using fishbone well design is to enlarge the reservoir's drainage area by intensifying interactions with fishbone-configured branches [11]. This method not only accelerates production but also ensures more cost-effective drilling and completion. Studies have validated fishbone wells as either an alternative to hydraulic fracturing or as a complementary method to enhance recovery in different reservoir areas [10].

In a comparative study, jetting emissions for FbD were found to be 6.7 tons per completion, significantly less than the 53.3 tons observed for acid-fracturing [12]. Moreover, drilling emissions for FbD were measured at 35.4 tons per completion, whereas propped-fracturing had a much larger footprint at 651 tons. These findings indicate that FbD is both environmentally and economically superior. FbD allows for the precise stimulation of high-yield reservoir areas and offers controlled connections with faults and fractures. The drive to investigate fishbone drilling in relation to CO_2 emission reduction arises from its ability to increase hydrocarbon production efficiency while lessening environmental impacts. By reducing energy and resource usage and decreasing the total number of necessary wells, fishbone drilling promotes a more sustainable hydrocarbon extraction method and assists in curbing CO_2 emissions, as highlighted by Ouadi et al. [13].

2. Fishbone Well Design Optimization

Ouadi et al. [13] highlighted the complexity and novelty of optimizing fishbone well path geometry in unconventional reservoirs. This process considers a range of factors, including the number of branches, their orientations, lengths, angles between the main borehole and micro-holes, and the distances between the fishbones, as shown in Figure 2. In response to the challenges posed by this technology, they proposed an innovative solution for extracting energy with a reduced CO_2 footprint. Ouadi et al. [14] demonstrated that the optimal design aims to maximize a project's economic return by boosting well productivity, which is achieved through increased reservoir contact. However, FbD's operational costs are typically higher than traditional drilling methods because of the complexity of the drilling operations. Numerous international case studies have analyzed the economic returns in terms of production gains compared to drilling expenses, including the work of Ouadi [15].

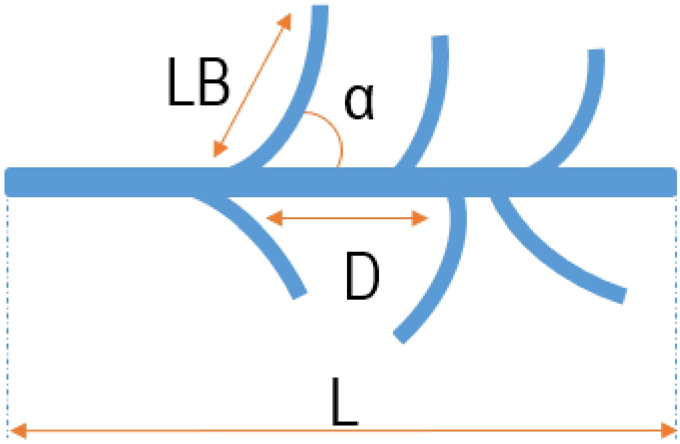


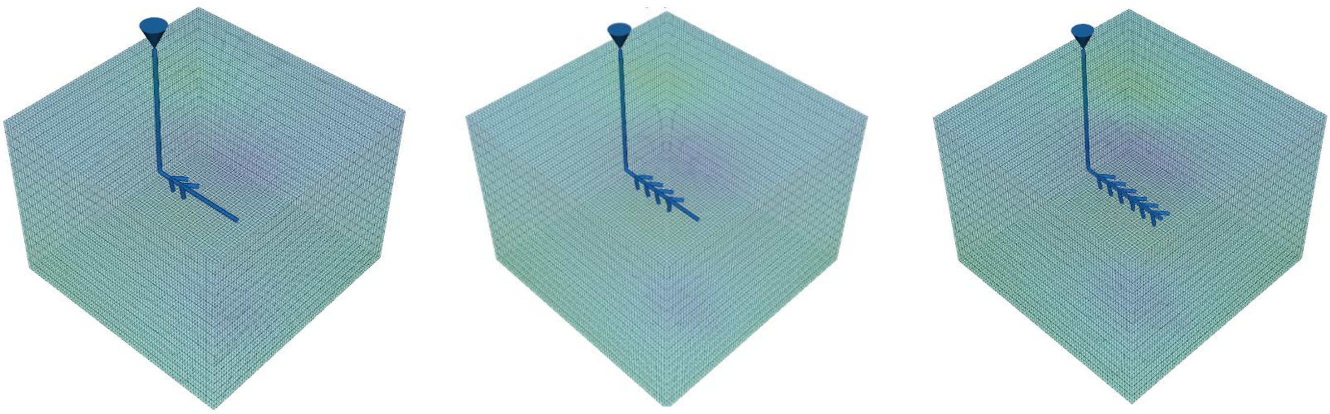
Figure 2. Fishbone well design, LB: length of the branch, α: angle between branch and main lateral, D: distance between branches, L: length of the main lateral of the fishbone [15].

Researchers have thoroughly studied various fishbone configurations using computer simulations, mathematical models, data-driven techniques, and direct observations. They have looked at how different fishbone well shapes affect how much of a reservoir can be recovered. The findings from these studies are detailed in the sections below.

2.1. Number of Branches and Their Direction

Researchers studied the link between the number of fishbone branches (n) and the oil production rate in a Middle Eastern oil field. They used detailed three-dimensional simulations and then carried out a sensitivity analysis (case #1). Their findings showed that when the number of branches increased to four, the oil production rate went up, but then it leveled off [16].

In a separate study (case #2), they examined production over time based on the number of branches. This study was on an extremely thin reservoir in the Daqing Peripheral Oil Field [11]. This particular well was known to be the thinnest fishbone drilling operation until 2012. The results from this simulation were consistent with the first study: as the number of branches increased, daily oil production improved. It seems the number of branches correlates with the reservoir size. When there is an ideal number of branches, most of the available oil in the reservoir is reached, as shown in Figure 3.



(**a**) (**b**) (**c**)

Figure 3. Comparative illustration of fishbone wells with varying branch numbers: (**a**): 4 branches, (**b**): 8 branches, and (**c**): 16 branches.

Increasing the number of branches boosts production, but it also raises drilling expenses. Thus, the ideal number of branches is where higher production rates meet with the fewest branches needed.

Xing et al. [11] looked into how the orientation of branches affects fishbone well productivity. In their study, all branches were of equal length, but the number and directions differed. They examined four scenarios:

1. Four branches, each spaced evenly around the well with a 30° angle to the main lateral.
2. Two branches on one side, each with a 30° angle to the main lateral.
3. Two branches on opposite sides, each with a 30° angle to the main lateral.
4. A single branch with a 30° angle to the main lateral.

Their findings showed that productivity was higher when branches were on opposite sides instead of the same side. In the second scenario, the best approach was to have four branches on different sides of the main hole, ensuring the most contact with the reservoir [11]. This suggests that branches on separate sides can tap into new areas of the reservoir, increasing the volume of oil reached.

Ouadi et al. [13] showed an increase in gas flow rates from their analytical model, numerical simulation, and empirical correlation as more branches were added as shown in Figure 4.

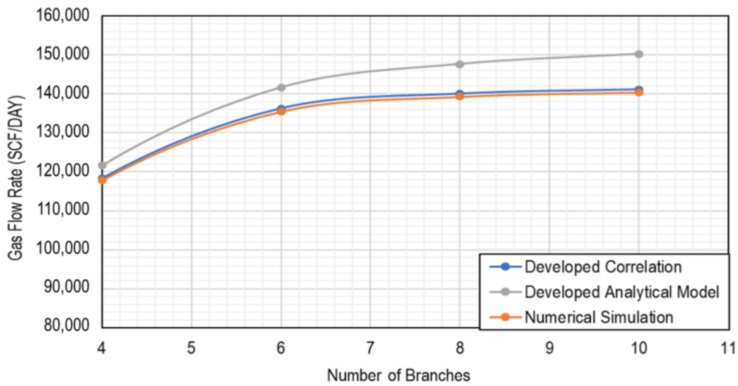


Figure 4. The effect of the number of branches on cumulative production (Ouadi et al. [13]).

2.2. Length of Branches

To determine the best branch length (L), Manshad et al. [16] ran a detailed analysis using a simulation model. They looked at fishbone wells with varying branch lengths, ranging from 100 to 450 m. The findings from case #1 showed that as the branch length grew, the initial daily production also increased. However, after reaching a branch length of 300 m, adding more length did not bring much more production.

In another study by Xing et al. [11] for case #2, the ideal branch length in the very thin reservoir turned out to be 200 m. It appears that the best branch length is influenced by the reservoir's physical characteristics and depth. If the branch is too long, it might touch the top parts of the reservoir that have poorer quality, as shown in Figure 5. After a certain branch length, there is little to no change in production. Ultimately, the aim is to get the most out of the reservoir while keeping drilling costs down.

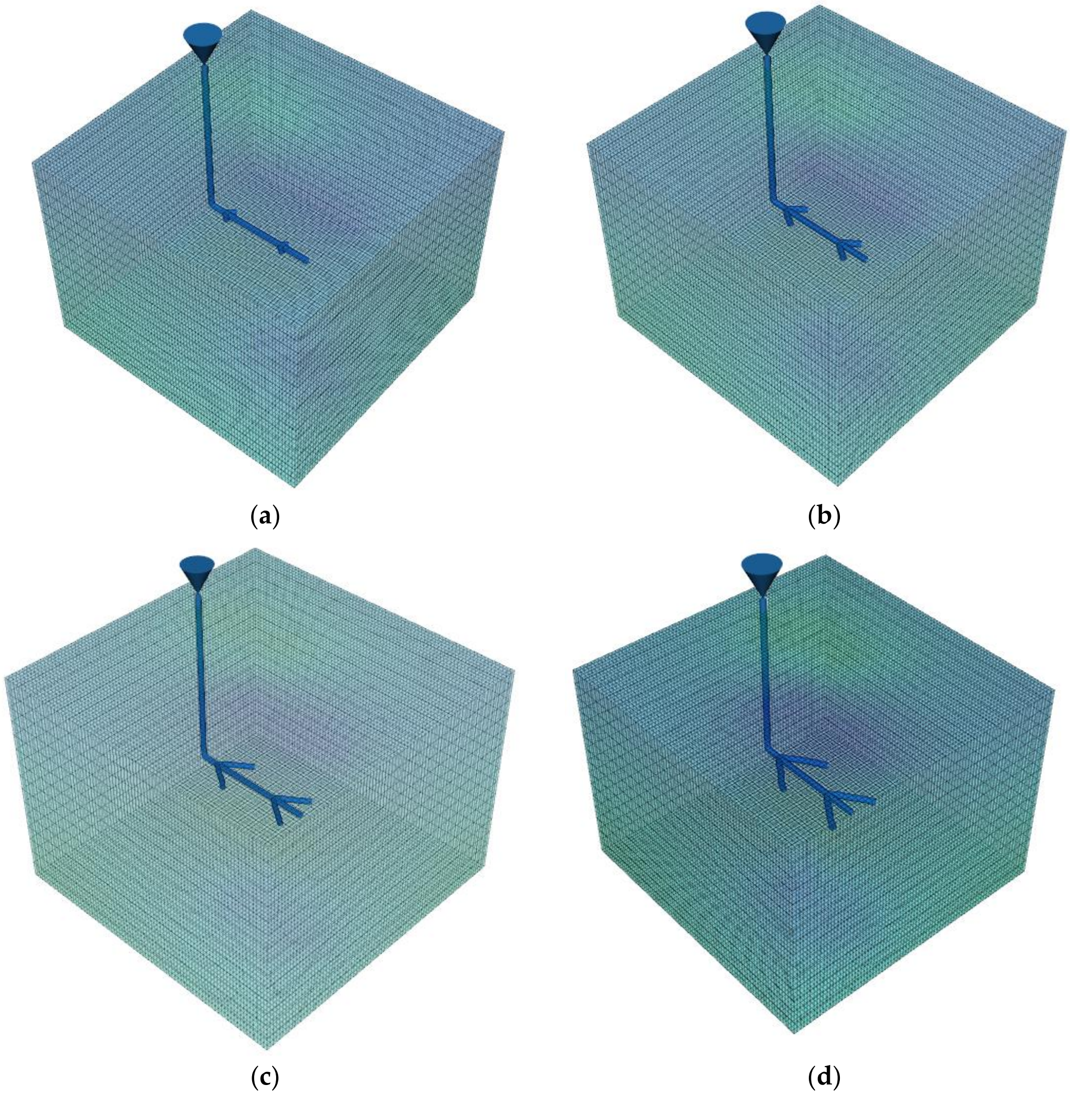


Figure 5. Comparative illustration of fishbone wells with varying lengths of branches: (**a**): 150 m, (**b**): 300 m, (**c**): 450 m, and (**d**): 600 m.

Sun et al. [17] applied analytical methods to study fishbone production in a scenario (case #3) where the combined length of the main borehole and branches in various designs was 800 m, with a 45-degree angle between the branch and the main borehole. Their findings showed the highest production rate when using two branch lengths: 100 m and 300 m. They noted that positioning the longer 300 m branch first ensured maximum contact with the initial part of the reservoir, allowing it to span the whole reservoir [17].

Ouadi et al. [13] observed that as branch lengths increased, flow rates also went up across numerical simulations, a modified correlation, and their new analytical model as shown in Figure 6. However, their study also found that when branches are spaced further apart, the area of the reservoir that is stimulated reduces, leading to a slight drop in flow rate. The data from the numerical model matched their correlation and showed a consistent pattern against the analytical model. Each of the models revealed a similar decline in productivity based on the distance between branches. This emphasized the influence branches have on each other, especially when spaced more than the drainage radius apart. The results underscore the importance of understanding how closely spaced branches might interfere with one another and affect a well's overall output.

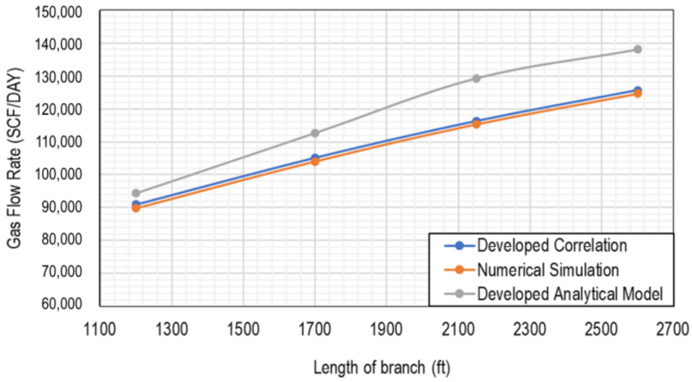
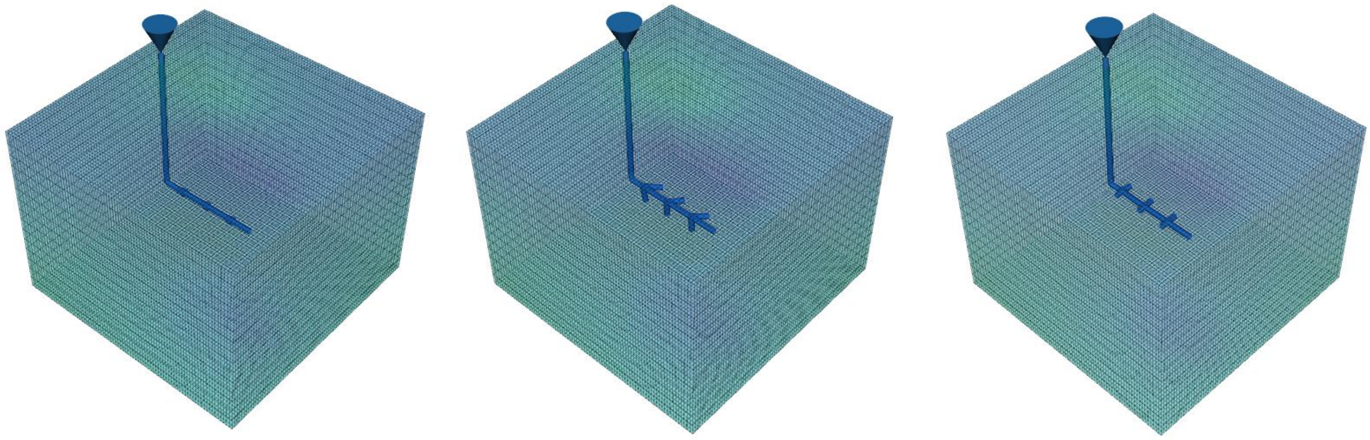


Figure 6. The effect of the length of branches on the cumulative production (Ouadi et al. [13]).

2.3. Branch Angles

Manshad et al. [16] used numerical simulations to study a fishbone design with four branches, each at different angles from the main horizontal borehole. They found that the best production rate in case #1 was when the angle of the branch was between 20° and 30°. Xing and his team [11] in their second study (case #2) examined the performance of four fishbone designs with varying angles between the branches and the primary well. Specifically, they looked at angles of 15°, 20°, 30°, and 45°. The production rates from these designs reinforced the findings from case #1, suggesting that angles below 30° for the branches did not significantly improve production.

Further, Sun and his team's [17] analytical model results showed that when all branching angles were the same, the fishbone well had the lowest production rate. However, productivity increased when the angles differed. In their third case (case #3), the combined angle was 135°, each branch was 200 m long, and the main borehole spanned 400 m. In summary, the effective area of the fishbone design expanded as the branch angle grew (Figure 7). This adjustment also affected the interaction between the branch and the main horizontal well. The interaction between various branch holes intensified up to an optimal angle.



(**a**) (**b**) (**c**)

Figure 7. Comparative illustration of fishbone wells with varying angles between the branch and the main lateral: (**a**): 20°, (**b**): 45°, and (**c**): 90°.

Ouadi et al. [13] discovered that variations in the branch angle have a minor influence on the production rate, with a small increase observed at 45° compared to the lowest production rate at 22° (See Figure 8). As the branch angle grows, the control area of the fishbone design expands until it reaches 45°, after which it declines slightly. Additionally, the angle change impacts the interference between the main horizontal well and the branch hole. The findings suggest that interference between distinct branch holes rises to an optimal point as the angle increases.

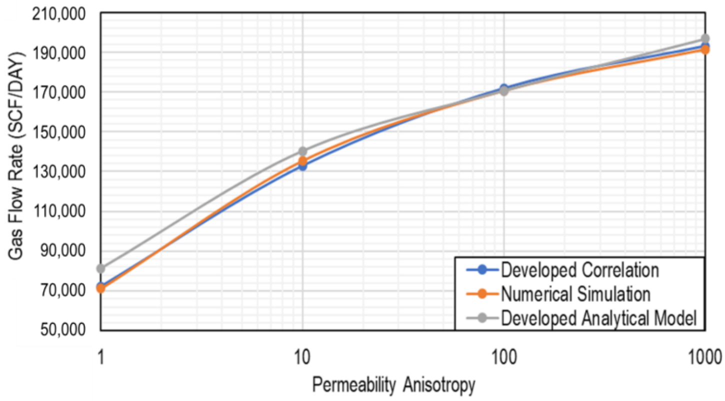
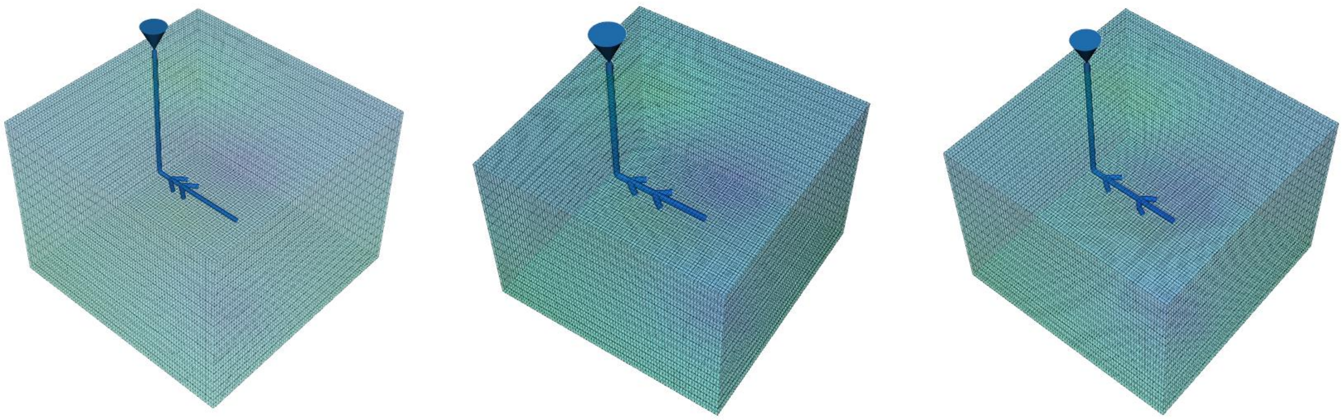


Figure 8. The effect of permeability anisotropy on cumulative production (Ouadi et al. [13]).

2.4. Distance between Adjacent Branches

Choosing the right branch Kickoff Point (KOP) involves considering various factors, including geological characteristics, the thickness of the formation, and the build-up radius (tied to the drilling strategy and deviation tools). It is essential to understand how branches intersect to ensure sufficient spacing for optimal drainage (Figure 9). Xing et al. [11] suggested a spacing range of 80 m to 150 m between adjacent branches. They analyzed four branch designs, each 200 m long, and a main borehole 400 m in length at a 45-degree angle. Sun et al. [17] used analytical models to study how the spacing between branches impacts daily production rates. Their findings indicated that wells were more productive when branches were positioned nearer to each other. Sun et al. [17] also observed that as the distance between branches grew, interference between them diminished.



(**a**) (**b**) (**c**)

Figure 9. Comparative illustration of fishbone wells with distance between branches: (**a**): 100 m, (**b**): 200 m, and (**c**): 300 m.

Ouadi et al. [13] found that increasing branch gaps led to reduced reservoir volume and a minor flow rate drop (Figure 10). Their numerical results aligned well with their correlation, differing consistently from their analytical model. All models showed reduced productivity with greater branch distance beyond the drainage radius.

In summary, optimizing fishbone well design is a complex task that requires considering several factors, including the number of branches, branch direction, branch length, branch angles, and distance between adjacent branches. Different researchers have studied these factors using numerical simulations, analytical and data-driven models, and empirical correlations. The key is to find a balance between maximizing reservoir contact and minimizing drilling costs to achieve the highest economic value for the project. As technology and understanding of unconventional reservoirs advance, fishbone well design will continue to evolve, and more efficient and cost-effective drilling methods will be developed.

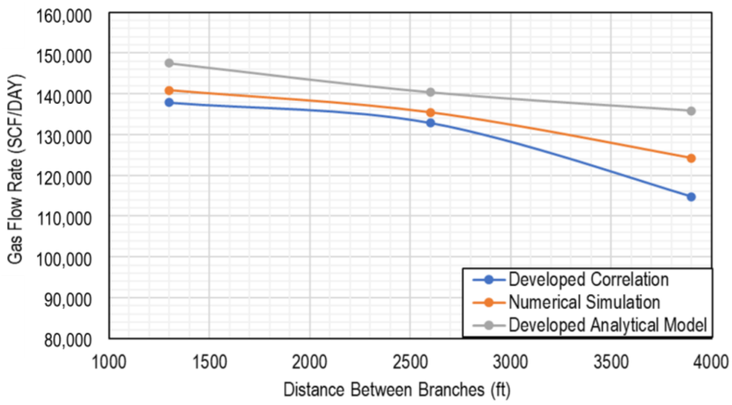


Figure 10. The effect of the distance between adjacent branches on the cumulative production (Ouadi et al. [13]).

3. Fishbone Technology Field Studies

Field studies offer the most reliable method for exploring the applicability of new engineering techniques, and it is strongly advised to calibrate simulations using experimental tests for each field application. Stalder et al. [18] reported a successful fishbone well drilled in Venezuela with nine branches, each approximately 900 m long, aiming to increase high-viscosity oil production by maximizing reservoir contact for improved fluid mobility. The reservoir's lithology in the Zuata field consisted of non-homogeneous sand with various barriers and permeable discontinuities. Results indicated increased well production accompanied by an 18% rise in drilling costs.

Manshad et al. [16] investigated fishbone design application in a giant Middle Eastern oil field with reservoir characteristics including a net pay thickness of 118 m at depths between 2709 and 2850 m, crude oil of 19.95° API, viscosity between 4.44 and 5.44 cP, and a Gas-to-Oil Ratio (GOR) ranging from 276 to 441 SCF/STB. The objective was to achieve 250 thousand Barrels of Oil Per Day (BOPD) based on the initial oil field development plan, marking the highest production plateau in the field.

Drilling a fishbone well served several environmental purposes: addressing the challenges of hydraulic fracturing near residential areas, preventing surface and underground water pollution, and increasing the recovery factor, which was around 19%, relatively low compared to other case studies [16]. The horizontal well section took 99 days to drill, with a mud weight between 1.22 and 1.25 gm/cm^3 and a KOP of 2974 m. Fishbone well path design in the Middle East led to a 393% increase in production, with drilling costs rising by 130% compared to a horizontal well. The optimal fishbone well features included four 300 m branches with a 30° deviation from the main horizontal well.

Various studies have shown the successful application of fishbone well designs in different regions and geological formations, including Russia's Vankorskoe Field [19], Abu Dhabi National Oil Company's (ADNOC) onshore field in a tight carbonate formation [20], Aasgard Field in Norway [21], and Vostochno-Messoyakskoye onshore field in Russia [22]. Productivity enhancements were also observed in the United Arab Emirates (UAE) with a 300% increase during the application of fishbone well technology in a very tight reservoir [23].

Several case studies have demonstrated the effectiveness of fishbone well designs in various geological settings and conditions, achieving productivity increases and successful stimulation of reservoirs [24–30]. These studies have also discussed drilling equipment, tools, and methods used for fishbone well drilling, such as the bottom hole assembly (BHA) consisting of a positive displacement motor (PDM), bend-sub, PDC bit, rotary steerable system (RSS), and logging while drilling (LWD) tools. Table 1 presents existing patents for fishbone well configurations.

4. Fishbone Technology Patents

The following Table 1 presents a summary of several patents related to fishbone well technologies. It includes the inventors, the date of the patent, the title of the patent, a brief description of the patent's purpose, and the source of each patent. This overview aims to highlight the advancements in fishbone well technology and its diverse applications in the field of oil and gas extraction.

Table 1. Summary of key patents in fishbone well technology and their applications.

Patent Date	Patent Title	Description	Source
22 October 2021	Fishbone Well Drilling Device and Drill Pipe Recovery Device	The patent describes an innovation in drill pipe for fishbone well drilling, which includes a shell and a central pipe to facilitate sliding.	[31]
6 April 2021	Fishbone-Structured Well for Natural Gas Hydrate Extraction	This patent discloses the use of fishbone wells for natural gas hydrate mining, where CO_2 is injected to break down the hydrate layers and extract from them.	[32]
8 October 2019	SAGD-Optimized Fishbone Well Design	This patent discusses the efficiency of fishbone well geometry for Steam-Assisted Gravity Drainage (SAGD) or steam-based oil recovery.	[33]
6 August 2019	Thermal Treatment of Fishbone Well Configurations	This patent highlights the effectiveness of fishbone well design for SAGD, specifically addressing challenges related to resistive heating.	[34]
22 April 2015	Multi-Lateral Fishbone Horizontal Well Drilling and Completion for Shale Gas Reservoirs	The patent describes the benefits of fishbone drilling in enhancing productivity in shale gas reservoirs, noting its cost-effectiveness and reduced environmental risk.	[35]
25 June 2013	In Situ Combustion with Fishbone Well Configuration	This patent defines the fishbone well's application for injection purposes, aiming to increase recovery through the in-situ combustion method.	[36]
9 September 2011	Drilling Completion Technology for Fishbone Branch Borehole	The patent outlines a method to prevent the collapse of micro-holes in fishbone well drilling, suggesting the use of a glass fiber-reinforced plastic casing.	[37]

5. Fishbone Drilling versus Conventional Drilling and Completions

5.1. Technical Considerations

According to the U.S. Environmental Protection Agency (EPA) [38], unconventional hydrocarbon resources are defined as resources that have become economically viable due to recent advancements in modern hydraulic fracturing and directional drilling techniques [39]. Unconventional reservoirs exhibit complex characteristics across various locations and sometimes within the same lithology. Numerous research and development projects have been launched to optimize recovery methods while considering technical and economic factors.

Horizontal drilling and hydraulic fracturing have significantly improved unconventional reservoir recovery as studied by Merzoug et al. [40]. Although this combination has been successful in providing access to previously inaccessible resources such as shale formations [41], they still suffer from some challenges. Multi-stage hydraulic fracturing in low permeability formations could suffer from rapid well productivity decrease due to fracture closure, lack of knowledge about fracture propagation, and proppant displacement issues [42–44]. Also, fracture initiation remains a concern, leading to fracture tortuosity, screen-outs, and uncontrollable fluid distribution between stages [45].

Fishbone well design, which uses multiple small branches in various directions to intersect natural fractures and maximize reservoir contact, can address these issues. The work presented by Ouadi [15] highlighted that this technology can offer the same advantages of horizontal drilling and hydraulic fracturing while saving time, reducing costs from an overall field development perspective, and increasing well productivity.

5.2. Environmental Considerations

The growing concern for environmental protection is driving researchers and the oil and gas industry to adopt more eco-friendly practices. Government-imposed environmental regulations have prompted the industry to improve the efficiency of drilling operations, particularly in the areas of waste management and disposal. Although the combination of horizontal drilling-hydraulic fracturing offers some advantages, it poses environmental risks such as high water consumption and potential groundwater contamination.

CO_2 emissions from drilling and completion operations originate from various sources, including the energy used to power the drilling rig and associated equipment, in addition to the supplies used during the process. Some of these sources include:

- Fuel consumption: The primary source of CO_2 emissions in drilling operations comes from the combustion of fossil fuels, which power the drilling rig, generators, and other equipment. Diesel and natural gas are the most commonly used fuels, and their combustion releases CO_2 into the atmosphere. Since rig generator sets operate continuously, fuel consumption represents the largest operational cost and environmental impact in drilling operations. Diesel engines are widely used in drilling and fracturing operations due to their reliability and versatility. However, they are associated with low efficiency and high emission levels. According to a study by Parks [46], for 1200 rpm generator sets rated at approximately 1100 kW, fuel consumption can reach up to 200 g of fuel per kW hr generated. One of the challenges faced in drilling operations is the fluctuating power requirements of the rig. Depending on the stage of the operation and the specific tasks being carried out, power demands can vary significantly [47]. This variation can lead to inefficiencies in fuel usage and increased emissions. Fishbone drilling can effectively reduce fuel consumption by enabling the achievement of the same production output with fewer wells drilled in a single location. This approach not only minimizes the energy required for drilling but also reduces the need for transportation and site preparation activities. Furthermore, the smaller surface footprint of fishbone wells leads to fewer drilling pads, access roads, and associated infrastructure, ultimately resulting in decreased fuel consumption during construction and maintenance.
- Cement production and usage: Cement is used to seal and secure the well casing in place. The production of cement is energy-intensive and generates CO_2 emissions through the calcination of limestone, which releases CO_2, and the combustion of fossil fuels during the manufacturing process. Approximately 1370 pounds of CO_2 are generated for each metric ton of cement produced [48]. With a simple calculation, we can find that the average emissions from cementing one horizontal well of 10,000 ft can reach 500 metric tons of CO_2. Additionally, the transportation of cement to the drilling site contributes to emissions. By using fishbone drilling, we can reduce cement usage in several ways. Drilling one fishbone well instead of multiple conventional wells for the same production output reduces the need for multiple well casings, which in turn, decreases the overall cement consumption. The branches in fishbone drilling are mainly open holes, which means there is no need for cementing these sections. This eliminates the need for additional cement that would typically be required in multilateral drilling operations.
- Drilling fluids and mud: Drilling fluids, including water-based mud, oil-based mud, and synthetic-based mud, are used to lubricate the drill bit, stabilize the wellbore, and remove drill cuttings. The production, transportation, and disposal of these fluids contribute to CO_2 emissions. To minimize the adverse effects on the environment, environmentally friendly drilling fluid additives are now being utilized in drilling operations [49]. The use of fishbone drilling can lead to a reduction in drilling mud consumption due to the smaller diameters of the micro-hole branches and the decreased number of wells required to achieve the same production levels. As a result, less drilling mud is needed to maintain wellbore stability and perform other necessary functions, ultimately lowering overall drilling mud usage.
- Hydraulic fracturing fluids: In hydraulic fracturing operations, large volumes of water, sand, and chemicals are mixed and pumped into the well to create fractures in the reservoir rock as stated by Chellal et al. [50]. The production, transportation, and disposal

of these fluids generate CO_2 emissions [51]. The use of fishbone drilling can potentially eliminate the need for hydraulic fracturing in certain situations. As explained previously, fishbone drilling creates a complex network of small branches that increase the contact area with the reservoir, allowing for better stimulation and production.

- Waste management and disposal: The management and disposal of waste generated during drilling operations, such as drill cuttings, used drilling fluids, and other waste materials, contribute to CO_2 emissions through transportation and waste treatment processes. Fishbone drilling contributes to waste reduction and more environmentally friendly drilling operations by drilling one well with multiple branches, thereby achieving similar or better production rates with fewer wells. The smaller diameter branches produce less drilling cuttings and mud, which decreases waste management and disposal requirements.

Overall, the CO_2 emissions associated with drilling operations and supplies are the result of various activities, including fuel combustion, material production, transportation, and waste management. Reducing these emissions requires a combination of technological innovations, efficiency improvements, and the adoption of cleaner energy sources.

6. Potential Applications of Fishbone Drilling

At present, fishbone well technology is predominantly utilized in the oil and gas sector, particularly for unconventional reservoirs. Nevertheless, considering the numerous advantages of this approach, it is essential to highlight its potential applicability across a wider range of energy types and operations, as suggested by Ouadi et al. [15]. Additionally, it is worth exploring less-studied applications within the oil and gas industry itself, further showcasing the versatility of fishbone well technology.

6.1. Fishbone Drilling for Oil and Gas

6.1.1. CO_2-EOR for Improved Recovery

FbD could be applied to improve recovery during CO_2 injection or waste fluid disposal in unconventional formations with low permeability and porosity [52]. Traditional injection techniques often fall short in displacing fluid and boosting reservoir pressure after it is depleted. The fishbone design offers new avenues for research, especially in the area of Carbon Dioxide-Based Water Alternating Gas (CO_2-WAG) injection. This method might improve fluid movement due to its high viscosity and increase recovery from tight formations, as pointed out by Al-Obaidi et al. [53]. For instance, in the Bakken oil system, primary recovery stands at a mere 3% to 5%—not cost-effective. However, with CO_2 injection, this recovery rate jumps to between 43% and 58%, even though a significant amount of reserves remain untapped [54]. There is a clear need for more research to gauge the practicality and cost-effectiveness of using fishbone designs in CO_2 injection processes.

6.1.2. Heavy Oil Reservoirs

FbD may offer advantages in SAGD technology for heavy oil extraction by supporting gravity drainage using injected steam near horizontal wells. This could lead to higher recovery rates, overcoming 60% of the total oil in place [55,56]. Innovative fishbone infill well pairs were developed and successfully applied in the McMurray oil sand formation in Canadian oil sands play [57]. These fishbone wells had to overcome challenges such as collapse risks in sidetrack junction points. Implementing FbD in SAGD technology requires further optimization and understanding of the interactions between the fishbone wells and steam injection process to maximize heavy oil recovery.

6.1.3. Coalbed Methane Reservoirs

Fishbone drilling (FbD) technology has promising potential for coalbed methane extraction, particularly in coal beds with low permeability and strength. Unlike traditional fracturing methods in vertical wells, FbD's micro-branches can offer more consistent results. A study by Ren et al. [58] compared gas output from hydraulic fracturing and fishbone wells in the Liulin block of the Ordos basin in central North China. The fractured well's gas output dropped sharply after starting, whereas the fishbone well's production stayed consistent for three years. The consistent surface contact in the fishbone well is likely the reason for its stable output. More studies are essential to understand FbD's potential in global coalbed methane reserves and its possible economic advantages.

6.1.4. Naturally Fractured Reservoirs (NFR) and Tight Formations

Drilling fishbone branches successfully in tight oil and gas formations could enhance production estimation, which is typically complicated in coalbed methane reservoirs due to low permeability and naturally fractured characteristics [59]. Successfully applying FbD in tight formations and coalbed methane reservoirs may lead to further advancements in drilling technology and overall productivity.

6.1.5. Gas Hydrate

The study conducted by He [60] primarily investigated the application of fishbone wells for the extraction of gas hydrates from reservoirs, using the Shenhu area of the South China Sea as a case study. The research indicated that whereas the use of horizontal wells significantly improved daily gas production, it still fell short of the minimum threshold required for commercial exploitation.

The findings suggest that fishbone wells with a higher number of branches lead to a more rapid rate of free water production, reservoir depressurization, and free gas production in the initial stage of development. It was observed that a six-branch fishbone well could increase cumulative gas production by 59.3% in comparison to a single horizontal well. Nonetheless, the study also acknowledged that hydrate dissociation, facilitated by the depressurization process, consumes significant heat, causing a swift drop in reservoir temperature and a reduced hydrate dissociation rate. The research proposes a combined approach of heat injection and depressurization in later stages of development to provide enough thermal energy for hydrate dissociation.

6.1.6. Refracturing and Depleted Reservoirs

Unconventional resources often see a quick drop in production, which might require further stimulation due to issues like fracture damage or decreased conductivity. Although refracturing is one solution, it comes with challenges in already depleted reservoirs. Issues like changed in situ stress, potential casing collapses, and shifts in perforation spots [61] can complicate predictions on fracture growth and orientation. Here is where fishbone drilling (FbD) can step in. FbD can intersect with existing fractures in these reservoirs, access untouched areas at a reduced cost, and offer an eco-friendlier approach compared to traditional methods.

6.2. Fishbone Drilling for Geothermal Applications

Geothermal energy is a renewable and sustainable energy source derived from the Earth's natural heat, originating from the radioactive decay of elements within the Earth's core and residual heat from the planet's formation. Once a viable geothermal resource is identified, production wells are drilled to access the hot fluids, which can be used for direct heating applications or to generate electricity through geothermal power plants [62].

Enhanced Geothermal Systems (EGS) are an advanced geothermal technology designed to unlock the potential of geothermal energy in areas with limited water resources or low natural permeability. In EGS, artificial fractures are created in the rock formations using techniques such as hydraulic stimulation. These fractures enhance the permeability of the rock, allowing water to circulate through the hot underground rocks to extract the heat, which can then be converted to electricity at the surface [62].

Fishbone drilling (FbD) can be beneficial for geothermal projects as it increases contact with the reservoir, leading to better heat transfer and steam production. Geothermal reservoirs often face issues like extreme temperatures, rough formations, broken rock, and harsh fluids, so new drilling approaches are needed (as shown in Figure 11). By using FbD, geothermal wells can be more efficient by combining one vertical and horizontal well with several branches, streamlining the drilling process and saving time. Additionally, FbD may induce microcracks in brittle geothermal reservoir formations using shockwaves after drilling, further improving heat exchange. To apply FbD technology in geothermal wells, new downhole designs that support the reservoir conditions must be investigated [57].

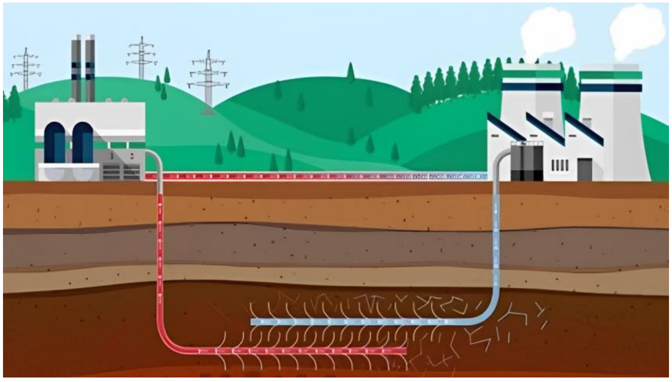


Figure 11. Fishbone for geothermal [12].

6.3. Fishbone Drilling for Underground Injection and Storage

FbD technology may be employed in water disposal, underground water and gas storage, and CO_2 sequestration projects. This technology can accelerate the rate of injection, increase formation adsorption, facilitate solution mining for salt caverns, and enable rapid water disposal operations. FbD provides access to more horizons compared to vertical or horizontal wells, achieving better connections between different salt-bedded formations with various thicknesses without destroying formation boundaries. These boundaries are crucial for confining underground stored fluids and preventing leakage into other zones, including aquifers.

FbD technology can also be applied to hydrogen storage projects, which is a growing area of interest in the transition to clean energy. Hydrogen storage in underground formations, such as salt caverns and depleted hydrocarbon reservoirs, requires efficient drilling and completion techniques to optimize storage capacity and ensure minimal leakage [63]. FbD can provide a more extensive connection between various underground formations, enhancing the storage potential and reducing the risk of hydrogen leakage. By drilling micro-branches, FbD can increase reservoir contact and improve the storage capabilities of these formations. Further research is needed to optimize the FbD technology for hydrogen storage applications, considering the unique characteristics of hydrogen, such as its small molecular size and the potential for embrittlement in certain materials (Figure 12).

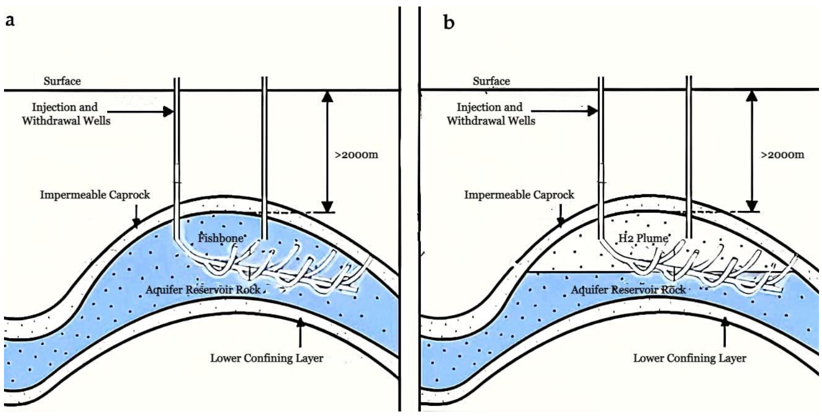


Figure 12. Fishbone for hydrogen storage in saline aquifers. (**a**) before injection, (**b**) post injection.

7. Contribution of Fishbone Drilling to Reduced CO_2 Emissions

The driving force for investigating fishbone drilling in the context of CO_2 emissions reduction is its ability to enhance hydrocarbon production efficiency while lessening the environmental footprint of drilling activities. Traditional drilling and stimulation methods, like hydraulic fracturing, often necessitate considerable energy and resource input, potentially increasing CO_2 emissions. Fishbone drilling, however, presents multiple benefits that can help in reducing CO_2 emissions:

- Improved reservoir contact: Fishbone drilling augments the contact surface between the wellbore and the reservoir, resulting in better hydrocarbon recovery efficiency. This increased efficiency may lead to a reduced number of wells needed to extract an equivalent amount of hydrocarbon resources, consequently diminishing the total drilling activities and related CO_2 emissions [64].
- Decreased resource utilization: Fishbone drilling could potentially reduce the dependency on hydraulic fracturing, which involves injecting vast amounts of water and chemicals into the ground as stated by Merzoug et al. [65]. By decreasing the reliance on hydraulic fracturing, fishbone drilling can lower the energy and resource consumption associated with drilling operations, thereby reducing CO_2 emissions.
- Reduced energy needs: Fishbone drilling can be integrated with underbalanced drilling or coiled tubing drilling as highlighted by the study of Ouadi et al. [15], both of which may demand less energy compared to conventional drilling techniques. These methods can help to decrease energy consumption during drilling, resulting in reduced CO_2 emissions.
- Enhanced well productivity: Fishbone drilling has the potential to boost well productivity, enabling more efficient hydrocarbon extraction with less carbon footprint as demonstrated in research by Ouadi et al. [14]. This heightened efficiency may lead to fewer wells and drilling operations necessary to extract an equivalent amount of hydrocarbon resources, ultimately contributing to a decline in CO_2 emissions related to drilling activities.

Fishbone drilling (FbD) often outperforms hydraulic fracturing, particularly in less permeable formations. Economically and environmentally, FbD stands out as a better choice, with added regulatory advantages [10]. A recent study by THREE60 Energy found that FbD methods greatly reduce CO_2 emissions compared to other well improvement methods. The study showed an 88% emissions drop using FbD's jetting process and a 95% drop with its drilling method compared to other available options.

8. Challenges and Prospects of Fishbone Wells

Fishbone drilling presents a captivating blend of opportunities and challenges. As it holds the promise of heightened reservoir interaction and productivity, it concurrently grapples with a slew of challenges, especially in its preliminary exploration phases. These challenges are diverse, encompassing operational facets like wellbore stability, control over drilling trajectory, and the intricacies of geosteering. When it comes to modeling, traditional analytical and empirical methods often fall short. However, the emergence of Computational Fluid Dynamics (CFD) heralds a hopeful era of solutions, though these too are not without their complexities. It is pertinent to note that many of these challenges might be exacerbated due to the paucity of research in this domain. Our perspective suggests that the recurring or anticipated problems are, in large measure, a manifestation of the existing research gaps. Through this section, we aim to dissect these challenges and prospects, providing a comprehensive understanding of the fishbone drilling landscape and charting possible future trajectories.

8.1. Operational Challenges

Fishbone technology is still in the early stages of exploration and development. A comprehensive comparison between multi-stage hydraulic fractured wells and fishbone wells needs to be conducted based on long-term productivity and economic factors [15].

Several challenges must be investigated for fishbone drilling (FbD) feasibility, including productivity quantification, production performance estimation, wellbore stability, interference between branches, drilling fluid effects, intersection with natural fractures, geosteering, and monitoring technologies, and potential integration with hydraulic fracturing operations. higher operational costs and difficulties in controlling the drilling trajectory [66]. Addressing these challenges will further advance fishbone technology and help determine its feasibility in comparison to hydraulic fracturing. Investigating the impact of drilling fluid, bottom hole assembly (BHA) choices, and drilling operation techniques can help avoid wellbore damage and improve well-cleaning challenges during the drilling of fishbone microbore holes. Advancements in fishbone geosteering technologies and monitoring methods for micro-hole branches and geometry detection are essential. Precise fishbone well placement is crucial since incorrect operations can result in connections with zones containing undesirable fluids, as well as difficulties in drilling through natural fractures.

8.2. Modelling Challenges

The complexity of fishbone well geometries is readily apparent, making their modeling a challenging task that must be approached carefully. A recent study by Ouadi et al. [13] compared analytical, empirical, and data-driven models to assess the performance of fishbone wells. Although data-driven models appeared to perform better than the other models, the study highlighted the limitations of all models in accurately modeling fishbone wells (Figure 13).

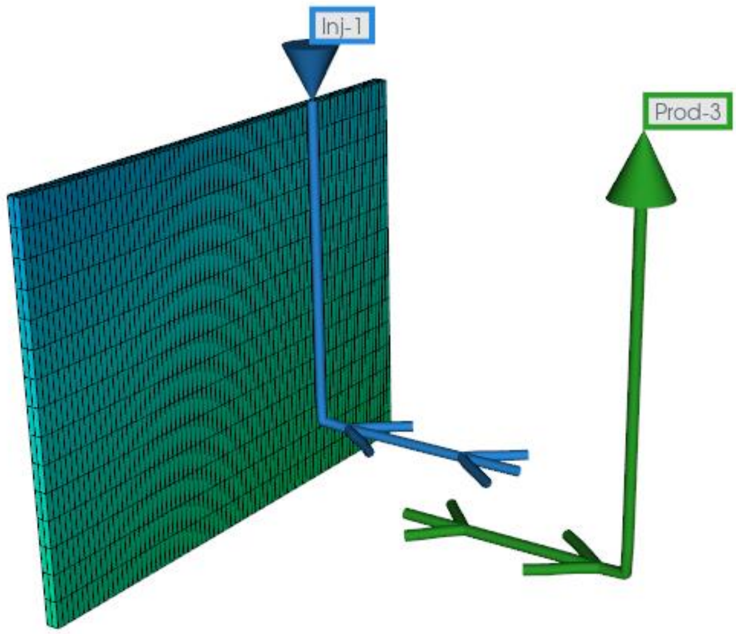


Figure 13. Advanced representation of fishbone well structures within a reservoir model.

Regardless of the application, whether it involves enhancing the production of oil and gas wells or injecting gas or water into a reservoir, it is crucial to analyze the performance of the wells in producing or injecting fluids. With newer applications, these challenges become even more complicated. Limited knowledge of these newer resources combined with conventional drilling and the complexities of fishbone wells makes it nearly impossible to model them using currently available analytical models due to the different physics involved. Empirical and data-driven models also fall short as they require experimental data to perform accurately.

Ensuring consistency in this context involves recognizing the limitations of current modeling approaches and focusing on the development of new models that can better account for the unique challenges posed by fishbone wells and their applications.

One promising approach to overcoming these limitations is the utilization of Computational Fluid Dynamics (CFD) modeling. CFD has the potential to provide more accurate and detailed insights into fluid flow within fishbone wells by solving the governing equations that describe the physics of fluid flow. This approach can account for various factors such as fluid properties, reservoir heterogeneity, and complex well geometries, which are often overlooked or simplified in analytical and empirical models [67]. Furthermore, CFD modeling allows for the inclusion of more advanced physics, such as multiphase flow, non-Newtonian fluid behavior, and the effects of temperature and pressure changes, which are crucial in complex applications such as EGS and hydrogen storage [68]. This enables a more comprehensive understanding of fishbone well performance and the prediction of potential issues that may arise during the production process.

Despite its advantages, it is essential to recognize that CFD modeling also comes with certain challenges, such as the need for high-performance computing resources and the requirement for expertise in numerical methods and fluid mechanics [69]. Nevertheless, by leveraging the power of CFD, researchers and industry professionals can gain a deeper understanding of fishbone well performance and develop more effective strategies for optimizing production in different energy resources.

8.3. Prospective Outlook on Fishbone Wells

The journey of fishbone drilling technology through its nascent stages is layered with intricate technical challenges and potential breakthroughs. Presently, operational difficulties such as wellbore stability, trajectory control, and geosteering underscore the need for advanced real-time monitoring systems and data-driven decision-making tools.

On the modeling frontier, whereas traditional analytical paradigms struggle to encapsulate the full spectrum of fishbone well dynamics, the burgeoning application of Computational Fluid Dynamics (CFD) is poised to revolutionize this space. However, to harness the full potential of CFD, it is essential to invest in high-performance computing resources and refine numerical methods to better represent the fluid mechanics specific to fishbone wells.

Another potential avenue for exploration is the fusion of machine learning (ML) algorithms with CFD to provide predictive analytics on well performance. This could mitigate the current shortcomings of empirical and data-driven models which require extensive experimental datasets. Additionally, the integration of advanced sensors within the wellbore could provide a continuous stream of data, paving the way for real-time optimization techniques.

The intersections of unconventional reservoirs with fishbone drilling also necessitate the development of specialized simulation tools. These tools should account for reservoir heterogeneities, multiphase flow dynamics, non-Newtonian fluid behavior, and the thermodynamics of processes like Enhanced Geothermal Systems (EGS) and Hydrogen storage.

In view of these technical complexities, the road ahead mandates a rigorous collaborative approach, bringing together reservoir engineers, computational scientists, drilling experts, and digital technologists. It is our conviction that the detailed exploration of these technical avenues will guide the future advancements and robust applications of fishbone well technology.

9. Conclusions

In summary, fishbone drilling (FbD) has emerged as a promising technique for enhancing wells. It presents a variety of advantages, including increased productivity, economic benefits, and reduced environmental impact. The optimized design of fishbone well paths, considering factors like the number of branches, their directions, lengths, angles, and spacing between them, plays a pivotal role in maximizing the efficiency and effectiveness of this drilling approach.

Recent studies have also emphasized the environmentally friendly aspect of FbD, resulting in notably lower CO_2 emissions compared to other well enhancement techniques.

This environmentally responsible approach, coupled with the potential for more cost-effective solutions, positions FbD as an appealing choice for the oil and gas industry.

Expanding its applications to other energy sectors, fishbone drilling can find utility in Enhanced Geothermal Systems (EGS), enhancing heat extraction efficiency and mitigating environmental risks compared to conventional methods. FbD also holds promise in hydrogen storage, aiding the development of underground storage facilities with enhanced connectivity and capacity.

This review paper establishes a groundwork for further research into the versatile applications of fishbone technology within the energy sector. As noted, the utilization of FbD should not be confined to enhancing production from unconventional reservoirs but should also encompass other energy systems, such as geothermal, carbon capture, utilization and storage (CCUS), and hydrogen storage. By merging the environmental advantages of these technologies with FbD, a significant contribution can be made towards reducing the overall carbon footprint.

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Nomenclature

FbD	Fishbone Drilling
CCUS	Carbon Capture, Utilization, and Storage
LB	Length of the branch
α	Angle between branch and main lateral
D	Distance between branches
L	Length of the main lateral of the fishbone
CO_2	Carbon dioxide
EPA	U.S. Environmental Protection Agency
API	American Petroleum Institute
GOR	Gas-to-Oil Ratio
BOPD	Barrels of Oil Per Day
SAGD	Steam-Assisted Gravity Drainage
LWD	Logging While Drilling
BHA	Bottom Hole Assembly
PDM	Positive Displacement Motor
RSS	Rotary Steerable System

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