Reveiw

A technical review of radial jet drilling

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Radial jet drilling (RJD) is an unconventional drilling technique that uses the jet energy of high velocity fluids to drill laterals with different geometries in both conventional and unconventional reservoirs. Many case studies available worldwide have proven RJD as a viable alternative to traditional stimulation techniques, especially in marginal fields. RJD has a lot of application in the oil and gas industry. It is a cost effective completion technique to reach the untapped sweet spots, by-pass damaged zones near wellbore, re-complete old wells, and many other applications. The present paper outlines the basics of newly developed radial jet drilling technology. Advances in technologies, developments, forces imposed, jet fluid hydraulics, procedures, applications, and challenges of RJD are reviewed in this paper. Simulation studies and several worldwide case studies are discussed to evaluate the RJD technology.

Key words: Radial jet, drilling, completion, laterals.

INTRODUCTION

Recently, the oil and gas industry has witnessed a steady increase in the use of short-radius horizontal drilling operations to enhance well productivity. The trend is expected to continue in the future as oil and gas industries become increasingly aware of the benefits associated with it while targeting thin reservoirs and oil reserves, which are pocketed and scattered. Horizontal drilling and new completion techniques have helped increase production in fields that may be uneconomic with traditional completions. However, these traditional techniques are still expensive and may not be suitable in marginal oil/gas reservoirs. Developing small and marginal fields with traditional techniques is expensive and economically unviable. For example, the cost can range from 1.0 to 10.0 million US$ to drill and complete

one well. In addition, with increase in oil usage and demand, the need for finding new reserves has very high importance. Only new discoveries cannot compensate the rate of exhaustion of resources. As 60% of the world's production is from matured fields, a better strategy to extend the production life of existing assets is crucial. Therefore new techniques, radial jet drilling, RJD, for example can be quite helpful in improving recovery, especially from marginal fields where the hydrocarbons reserves may not justify the high cost of horizontal drilling and hydraulic fracturing.

Abrasive water jet cutting of material involves the effect of a high-pressure velocity jet of water with induced abrasive particle. It is a recent non-traditional machining process, and is widely used in many industrial

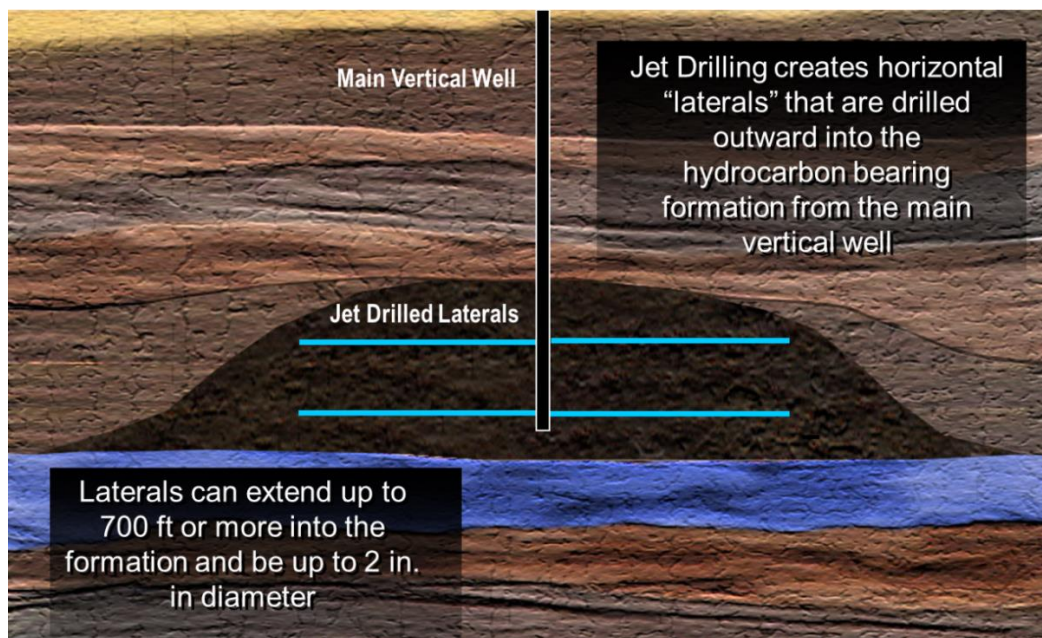E-mail: Kamel_a@utpb.edu. Tel: (432) 552 – 2219. Fax: (432) 552 – 2174.

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

applications such as mining, shipbuilding, automotive, etc (Brooks and Summers, 1969).

The concept of water jet was first introduced in the 1960s and the initial applications were limited to cleaning and unblocking drains. With the development of new technology and availability of high-pressure pumps, water jetting gained importance and was used on commercial scale to cut soft materials such as cardboard and rubber. Many efforts were made in late 1960s to use water jetting in petroleum industry to drill sub-surface reservoir rocks, but favorable results could not be achieved because of deficient abrasive injection techniques (Birtu and Avramescu, 2012).

Drilling fluids pumped under ultra-high pressures can enhance drilling performance while maintaining conventional rig operating procedures and safety. The impact of the high velocity fluid stream can significantly assist the mechanical action of the rock bit allowing penetration rates of 2 to 5-times over conventional systems in comparable drilling conditions (Pervez et al., 2012).

Dickinson et al. (1993) reamed a large casing and pushed 1¼-inch coiled tubing between 25 to 150 ft (7.6 to 46 m) into formation for production enhancement (2 to 10 folds). Currently, RJD has been proven to enhance production rates, reduce decline rates, reduce near wellbore damage, and to recover more resources from stripper wells (Dickinson and Dickinson, 1985; Dickinson et al., 1990, 1993; Abdel-Ghany et al., 2011).

Radial Jet enhancement has made it feasible to enhance production from more than 1.7 million wells that would otherwise be cost prohibitive to recover. This represents a total potential untapped market of more than $50 billion. Using RJD technology, horizontal channels up to 300 ft (91 m) can be drilled out from an existing wellbore in any direction, with 1 to 2 inches (2.54 to 5.1 cm) diameter using high-pressure fluid. In North and South America, RJD technology is oriented toward existing oil and gas wells at depths of 4,500 ft (1372 m) and shallower for productivity improvement (Cinelli and Kamel, 2013; Kamel, 2016).

RADIAL JET DRILLING (RJD)

Abrasive water jet cutting is one of the non-traditional cutting processes capable of cutting wide range of hard-to-soft materials. Radial jet drilling is a process of drilling radials of small bending diameter horizontal perforations using water jets at very high pressure in different directions. The diameter of these radials is approximately 1 to 2 inches (2.54 to 5.1 cm) and lengths up to 300 ft (91 m). These radials can be drilled in multiple layers through same well (Figure 1). Abrasive water jet process includes large number of parameters, which affects the quality of cutting surface. These parameters include hydraulic pressure, traverse speed, stand-off distance, abrasive mass flow rate, abrasive materials, nozzle length and diameter, orifice diameter, abrasive shape, size and hardness (Ragab and Kamel, 2013; Patel and Shaikh, 2015).

This drilling process encompasses a wide variety of systems and concepts ranging from downhole tools to be added to a conventional rotary system to the use of
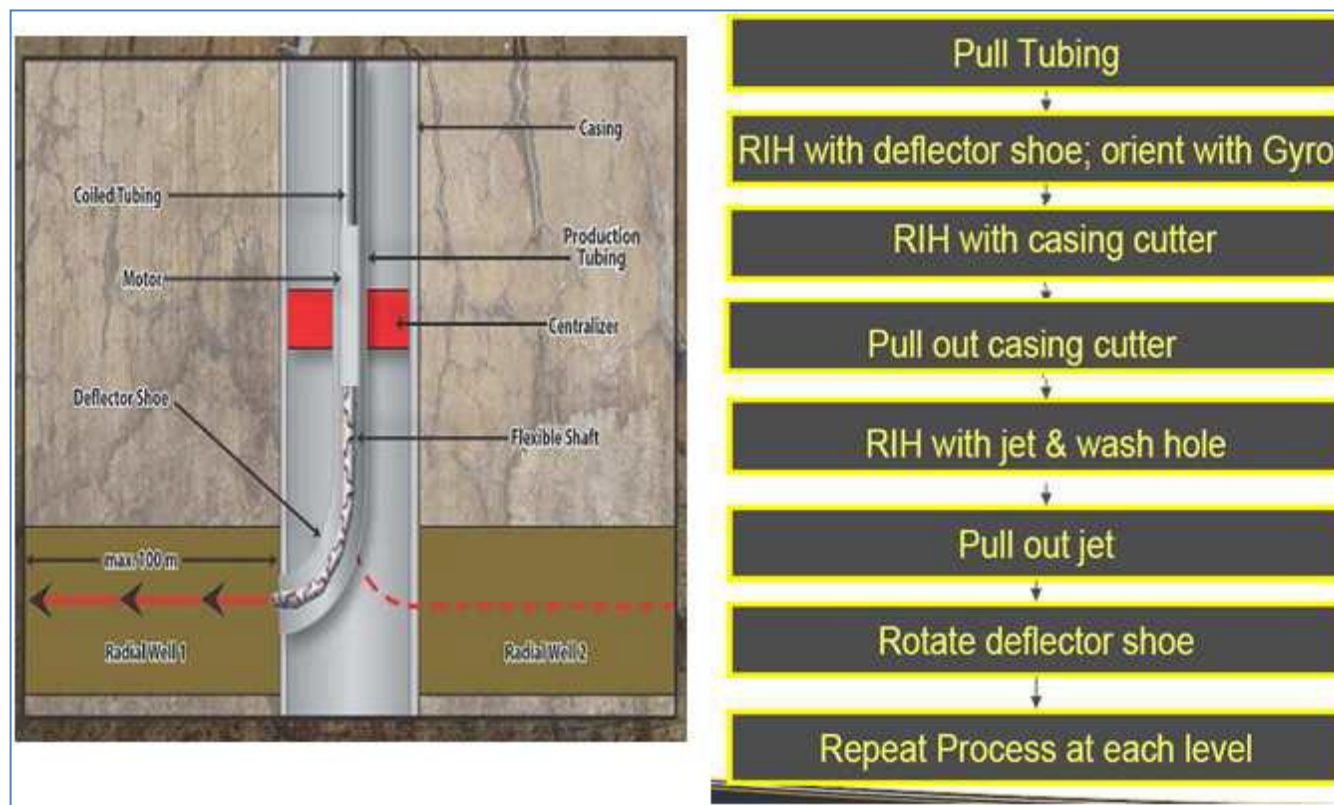
Figure 2. RJD procedure (Courtesy of RadJet).

surface pressure intensifiers with a parallel high-pressure flow path to completely new rigs designed specifically for jet-assisted drilling. Abrasive waterjet systems cut when the abrasive is accelerated above a critical velocity and the abrasive particles begin to chip out pieces of the target material upon collision. The higher the velocity, the more effective the cutting becomes (Al-Marahleh, 2015). When jet impact pressure and nozzle type is fixed, hole depth and rock breaking volume increases, and then decreases with the increase of standoff distance. The optimal standoff distance is 0.47 inch (12.0 mm) in the experiment (Wells and Pessier, 2003).

RJD process

Radial jet drilling is a cost-effective alternative way to drill small-size laterals using a coiled tubing unit. It eliminates the need for the conventional bit and mud system. In RJD, high-pressurized fluid is circulated through forward and backward nozzles connected to a high-pressure hose. The energized fluid leaving the forward nozzles is used to erode and drill the formation while the fluid leaving the backward nozzles is used to push the nozzle forward and to widen the laterals drilled (Abdel-Ghany et al., 2011; Cinelli and Kamel, 2013).

The RJD process is outlined in Figures 2 and 3 and

starts by removing the production equipment from the well. In cased holes, a cutter should be lowered to open a hole through both casing and cement while in open-hole completion, there is no need for a cutter and RJD process starts without the need for a cutter. A deflector shoe is then lowered into the well using coiled tubing unit to reach the target and oriented using gyro. The system starts circulating fluid under high pressure through the high-pressure hose and then exits the nozzle at very high speed to erode and drill laterals, push nozzles into the laterals, and widen the drilled laterals. Once a lateral is drilled, pressure is decreased and the hose is removed. This process can be repeated as needed to drill more laterals (Zhonghou et al., 1999; Gensheng et al., 2010; Marbun et al., 2011; Cinelli and Kamel, 2013).

RJD mechanism

The basic cutting mechanism is by using an array of nozzles in a drill head. Each nozzle has jetting fluids with necessary additives running through it with very high exit velocities of 1000 fps (305 m/s) and creating a drawdown of 10,000 psia (6.9×10^7 Pa.) These high-pressure jets cut through the formation employing various penetration mechanisms including superficial erosion, failure resulting from pore-elastic tension, and cavitation. As shown in
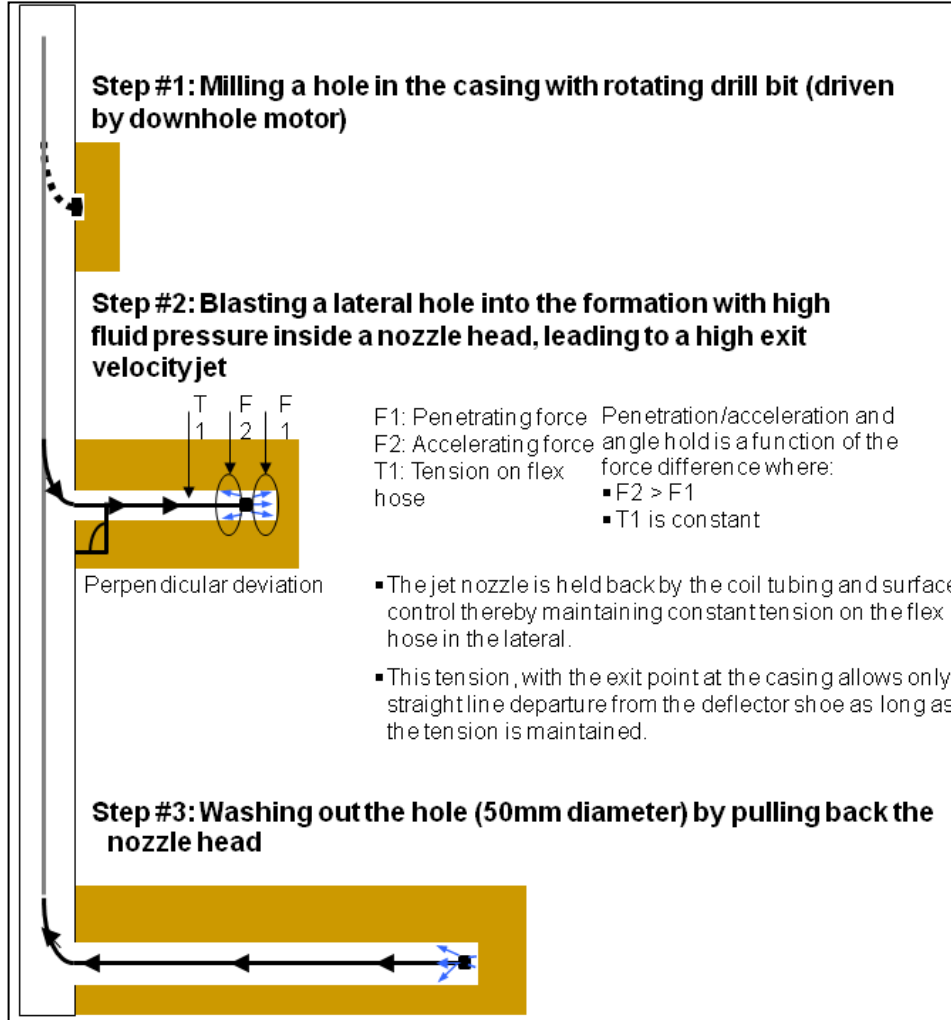
Figure 3. RJD steps sequence (Courtesy of RadJet).

Figures 4, 5 and 6 due to the distribution of nozzles in drill head, enough force is available to let the drill head slide into the lateral perforation created by water jets. There are four forces affecting the jet nozzle and flexible hose; fluids pressure on the forward surface of jet nozzle, F_{p-out}; friction force between wellbore and deflector, F_{df}; friction force between wellbore and flexible hose, F_f; and ejecting force generated by fluid jetting from orifices and acting on rocks, F_j. The forces along the x-axis can then be written as:

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

F_{df} is insignificant when compared to other forces and is therefore neglected. This reduces the above equation to:

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

The remaining forces are defined as follows:

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

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

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

As long as the pulling force is positive, the well can extend forward. This continues until the friction forces increase at a certain well length, l_{dh}, which results in a zero value for pulling force. At this point, the well cannot extend anymore and the well has reached its maximum length (Guo et al., 2009; Huanpeng et al., 2013; Ragab, 2013).

RJD tools

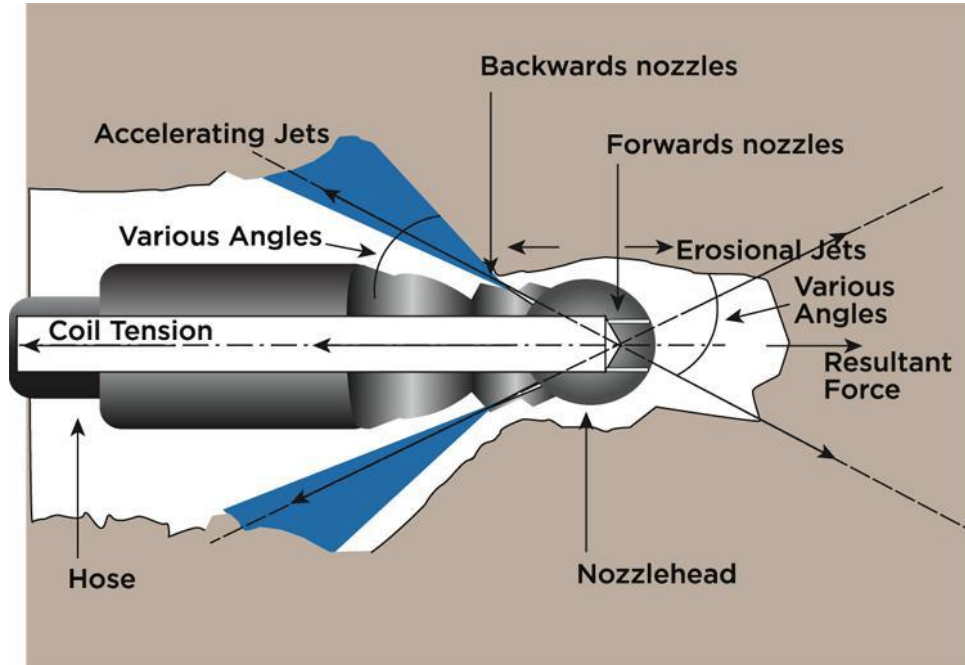Holes in casing and cement can be drilled using several
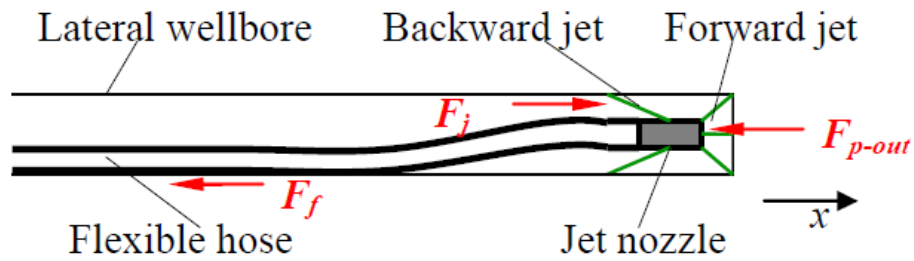
Figure 4. Sketch of the Nozzle

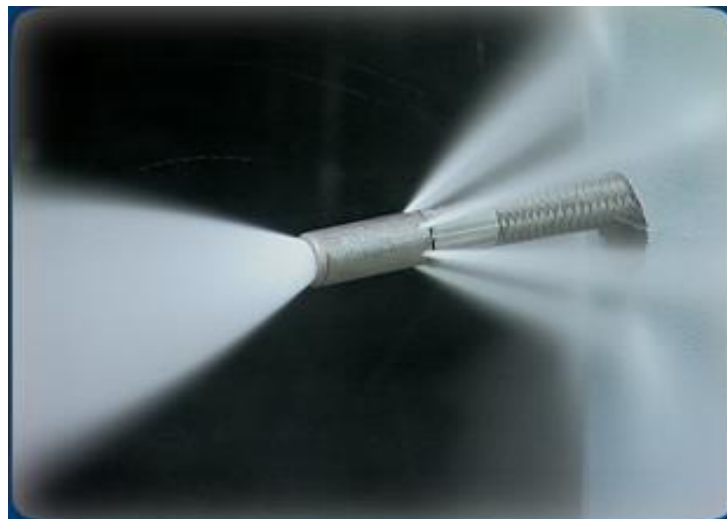**Figure 5.** Force analysis of RJD system.

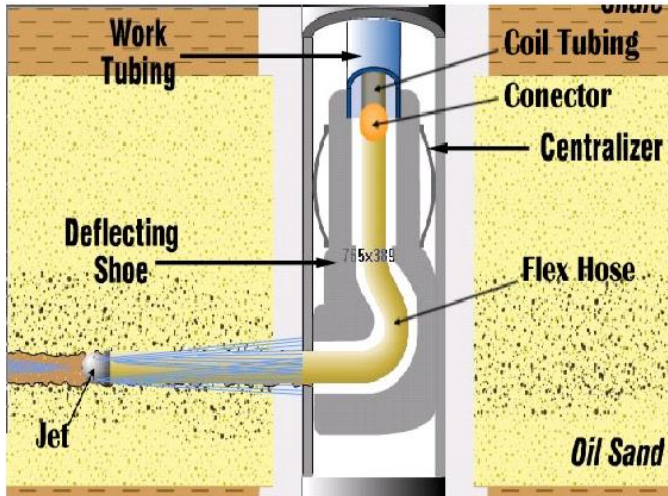**Figure 6.** Forward and backward nozzles (Courtesy of RadJet).

Figure 7. RJD downhole equipment.

techniques from cutter to energized fluid containing abrasive materials. The jetting nozzle is normally between ½-in and ¾-in (1.27 to 1.9 cm) in diameter with a length of 1.0-in (2.54 cm) and contains a number of forward orifices to allow fluid to drill through formation and backward orifices to allow fluid to widen the lateral and push the nozzle forward (Dickinson et al., 1992; Cinelli and Kamel, 2013). The hardware used are bottom hole assembly consisting of casing cutter, small diameter bit, mud motor, hydraulic piston along with auxiliary tools of tubing end connector, anchor, orienter, steering tool, controller (Figure 7). In addition, a coiled tubing unit is used to convey the drilling process from the surface (Kohar and Gogoi, 2014). The equipment connection diagram is shown in Figure 8 (Gang et al., 2013).

RJD fluids

In RJD process, fluids with abrasive particles or grains are circulated against the surface so that each particle cuts away a small bit of material. The fluid generally has an important indirect role. It stores and transfers the energy required to accelerate abrasive particles, guides the abrasive particles and focuses impacts within a small spot, flushes debris and abrasive particles away from the working zone, and ensures that fresh surface material is always exposed. In addition, it provides some lubrication between the particle and formation, reduces frictional heating, and provides an effective convection-cooling medium where heat generated during deformation is immediately extracted from the formation (Al-Marahleh, 2015).

Cinelli and Kamel (2013) discussed the RJD fluids in details. Briefly, in RJD process, various fluids can be used and the candidate fluid depends on both formation rock and fluids properties. Water is considered the most common RJD fluid, as its advantages over other fluids

are obvious. In cases where water is not an option, like water-sensitive formations, diesel is a viable alternative to avoid swelling problems. It also enhance penetration rate due to its solvent properties, especially with paraffinic crude oils. Acids like hydrochloric acid are good candidates for carbonate formations as it reacts and dissolves carbonate formations.

Hydraulics

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

$$\Delta P_{pump} = \Delta P_{CT} + \Delta P_{ST} + \Delta P_{hose} + \Delta P_{bit} \qquad (6)$$

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

$$\Delta P_{CT} \text{ or } \Delta P_{ST} = \frac{f_f \rho l_t v^2}{d_i} \qquad (7)$$

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

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

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

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

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

Applications of RJD

The ability of an abrasive assisted water jet to cut through rocks and metals has potential applications in the oilfield. In oil and gas industry, radial jet can be used to increase the drainage surface area and enhance oil production. In drilling, the high-pressure jet-drilling system can dramatically reduce the torque and thrust required for drilling, thereby increasing reliability, drilling rate of penetration (ROP), and lateral reach, which eventually
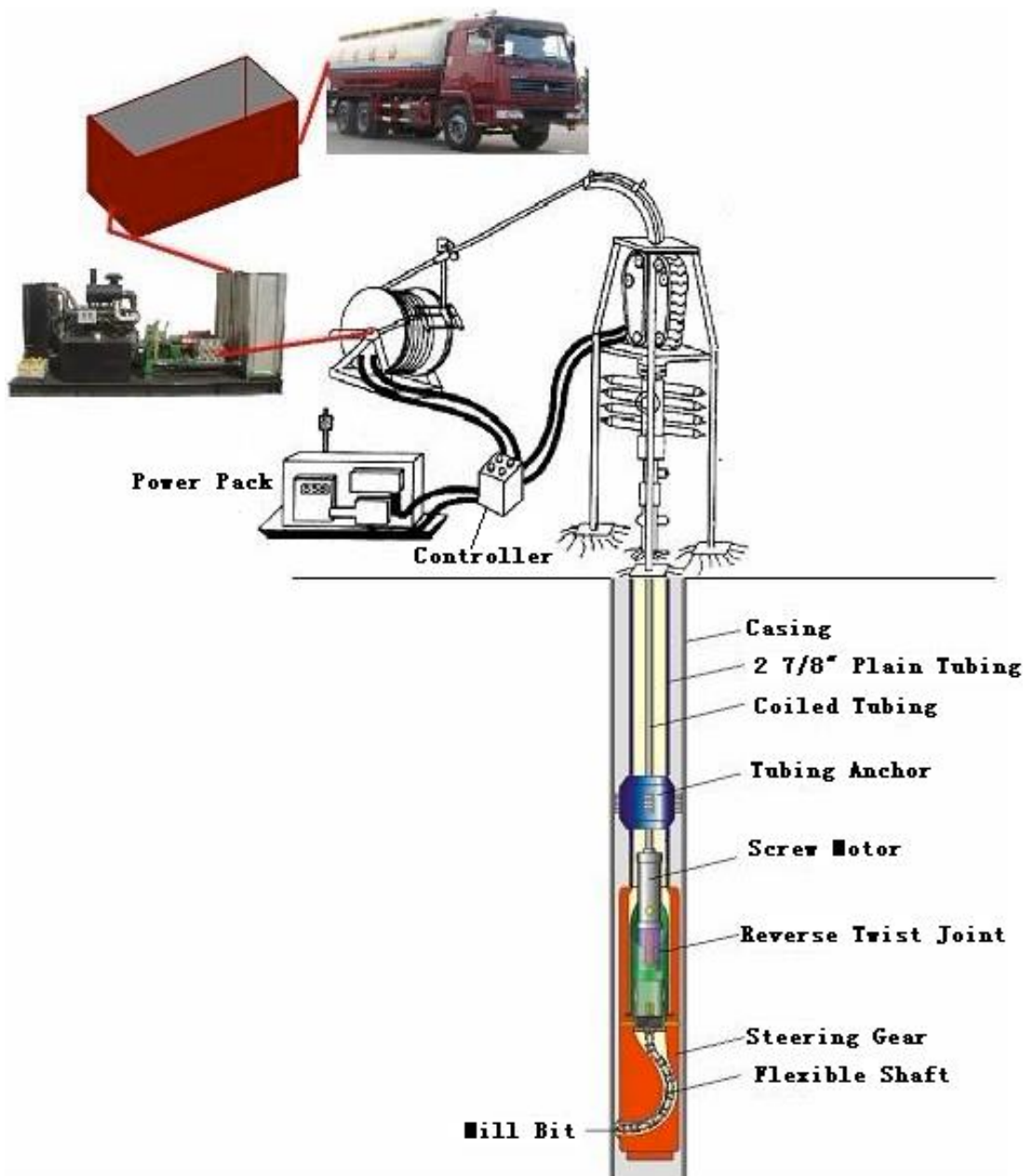
Figure 8. Equipment connection diagram.

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

(Ragab, 2013). This technique can be applied in different disciplines in oil well industry such as:

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

Advantages of RJD

Radial drilling is characterized by small footprint and minimization of the formation damage which can be used as a replacement for well stimulation through laterals and for cost reduction by minimizing the logging expense. RJD is economical, as it can be a cost effective method to complete vertical wells to perform like an open hole horizontal completion. In addition and based on what have been performed on some worldwide fields, the radial drilling methods have some economical and technical benefits such as (Dickinson and Dickinson, 1985; Bruni et al., 2007):

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

Limitations of RJD

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

1. Difficulties of penetration under porosity of 3 to 4%;
2. Maximum working depth about 4000 to 9000 ft (1220 to 2740 m);
3. Bottom hole temperature not to exceed 248°F (120°C);
4. Maximum wellbore inclination 30° and no more than 15° at the zone target depth/zone of interest;
5. Maximum tensile strength 100,000 psi (7×10^8 Pa.);
6. There is no way to complete the lateral with a liner.
7. Reentering the lateral after it has been drilled could be very tricky;
8. There are no surveillance options inside the lateral;
9. Standard logging tools likely will not fit into the lateral;
10. Directional control of the lateral is also very difficult;
11. Laterals can prematurely terminate due to fractures, faults, or other reservoir heterogeneities.

SIMULATION RESULTS

A simulation study was carried out on wells with different scenarios to accommodate a variety of reservoir permeability from high to low permeability values as shown in Figures 9 and 10 and forecasted an increase of productivity index with different number of laterals drilled as shown in Table 1 (Abdel-Ghany et al., 2011). As can be seen from these figures, the results show almost a triple fold of increase (FOI) in both high and low permeability formations. In addition, FOI depends on both number and length of laterals drilled. This confirms that RJD is a viable option for production enhancement.

Case studies

Case study #1: The Donelson West Field, USA

Cinelli and Kamel (2013) presented the case study of Donelson West Field, which contains 1,200 acres reservoir of limestone in Cowley County, KS. Its permeability is between 1.0 and 10.0 mD and its porosity is between 15 and 20%. The formation thickness is between 6 and 10 ft. The production history of this field can be traced back to 1968 where 13 wells produced a cumulative oil of 83,000 bbl. Afterwards, production declined quickly and in 1973, the cumulative production was about 15,000 bbl. Recently, the average production was about 1,000 bbl annually between the years of 2000 and 2009.

Development plan: Due to its declining history, despite of its high potential, a development plan was adopted in 2010 to stimulate the old wells and drill new ones. Eight old wells were reentered where laterals were jetted with RJD. In addition, two new wells were drilled and also jetted with RJD. After laterals were finished, all wells were hydraulically treated with equal quantities of acid and nitrogen. Afterwards, production started (Cinelli and Kamel, 2013).

Results: The two new wells with seven old wells showed a significantly improved production. The last well of the old ones did not show any production at all as it was drilled west of the field where the formation is normally very thin. Considering the low pressure, these could be the reasons why this well did not produce any hydrocarbons. However, production from the two new
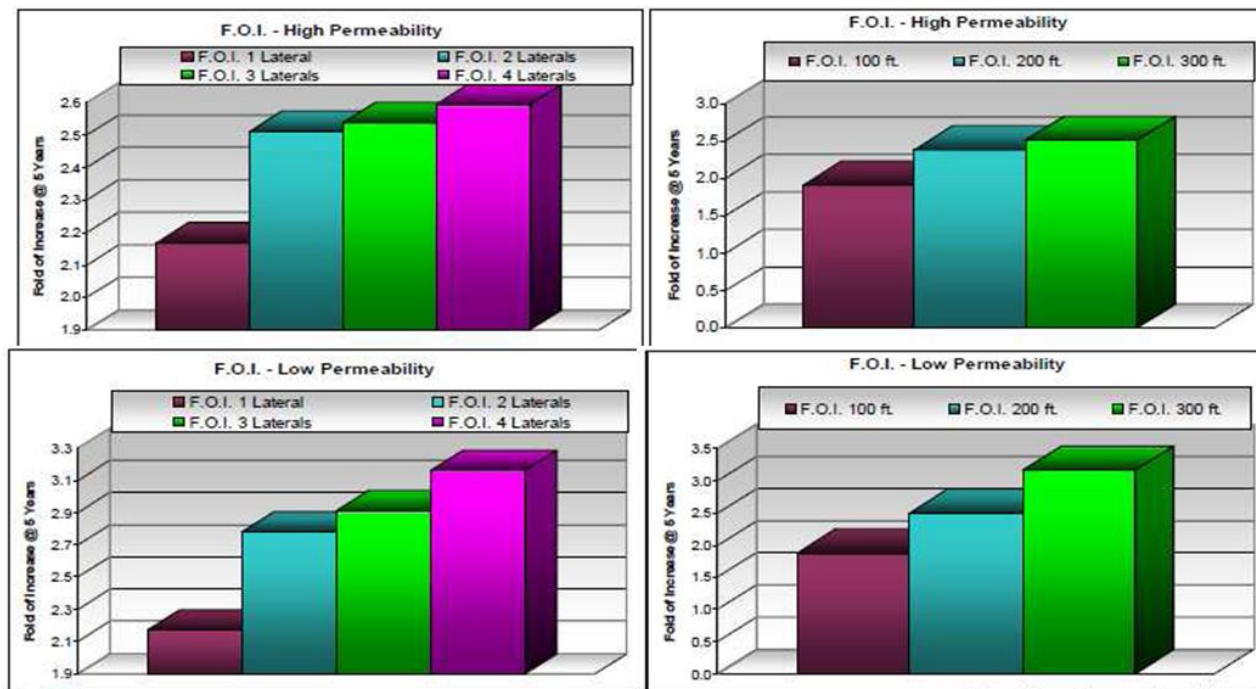
Figure 9. Fold of increase (FOI) for low and high permeability reservoirs.
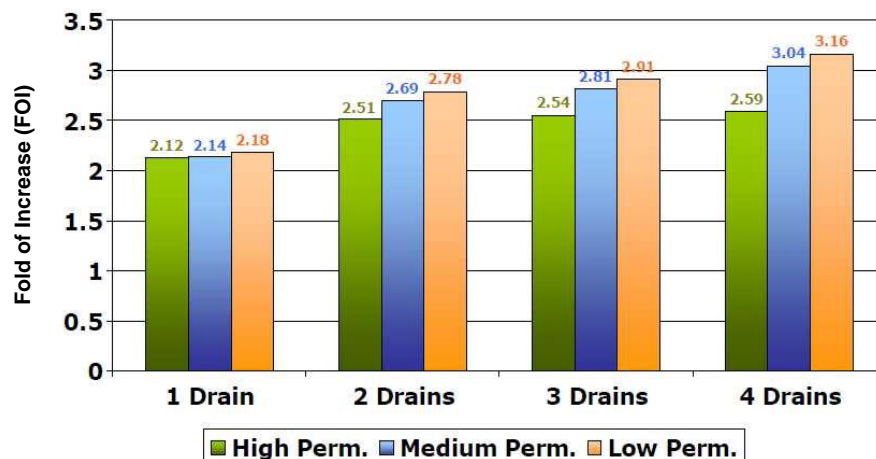

Figure 10. Fold of Increase (FOI) for different number of laterals.

wells and the old seven wells was exceptional. A summary of the field production before and after the treatment is shown in Table 1. As can be seen, the monthly production bounced from 197 bbl, with an average production of 157 bbl before treatment to 1100 bbl, with an average production of 938 bbl right after the treatment.

Finally, and despite losing one well, the results show a significant effect of the treatment which confirms RJD as a viable alternative technique for production enhancement

in old fields (Cinelli and Kamel, 2013).

Case study #2: Belayim Land Field, Egypt

The field is located in the central part of the Gulf of Suez, along the coast of the Sinai Peninsula and it is a multilayer field with separated reservoirs with interbedded shales and anhydrite intercalations.

Development plan: Radial drilling pilot tests were

Table 1. Pre-workover and post-workover production.

Before RJD		After RJD	
Year	bbl./month	Months After	bbl./month
2002	11	1	1100
2003	62	2	974
2004	125	3	976
2005	106	4	961
2006	85	5	789
2007	70	6	790
2008	133	7	1124
2009	142	8	797
2010	197	9	803
Average:	**157 (last 3 year)**		**938**

performed in three wells. In the first well (Well #1), 6 lateral drains were jetted at two main depths; three of them at 7460 ft (2274 m) and the other three were at 7450 ft (2271 m). Five laterals were 160 ft (49 m) long and the last one was 330 ft (101 m) long. In the second well (Well #2), 7 lateral drains, 160 ft (48 m) long were jetted with between 7650 and 7700 ft (2332 to 2347 m) depth. For the third well (Well #3), 4 laterals, 160 ft (49 m) long each were drilled; two at a depth of 7500 ft (2286 m) and the other two were at a depth of 8080 ft (2463 m).

Results: Well #1 showed an increase in production rate from 470 to 820 barrel oil per day, BOPD (about 350 BOPD gain) while there was no change in water cut. For well #2, RJD drilling was not as effective as in case of well #1. It only showed a slight increase in production from 233 to 246 BOPD. For well #3, there was no increase in production rate and this is believed to be due to the sand production problems. Well #3 has a history of sand production problems, which may plug laterals after being drilled. Well #2 and #3 were drilled in unconsolidated sandstone with a history of sand production and fines migration. This is one of the drawbacks of RJD, as it is not recommended for application in unconsolidated sand (Abdel-Ghany et al., 2011; Ragab, 2013).

Case study #3: K-block, Tarim Field, China

This is a condensate gas field producing since 1977 from a thin net pay of siltstone with low permeability and significant formation damage because of mud during drilling and completing operations.

Development plan: In 2010, a radial jet drilling plan was carried out to enhance the field production. The original pipe string was tripped out, workover operation was conducted, and then, RJD tools were lowered down to drill laterals.

Results: The data after RJD operations showed a significant enhancement in production. About 300% increase in oil production was obtained and even more, the field started to produce gas (Lu et al., 2014).

Further research

RJD, however, is a relatively recent technology in the oil and gas industry and still needs a lot of investigation and research to overcome its limitations and to explore new applications. For example, further research and testing of the jet nozzle penetration mechanism are required in order to identify the optimal nozzle configurations. New techniques are recommended to maintain the increase in production rate, especially in unconsolidated formation. Other areas for improvement from the author point of view include improved jet bits (most crucial), high strength materials and tubular goods, fluids and application of drag reduction concepts, alternative methods to clean laterals from cutting after jetting process.

CONCLUSION

Despite its limitations, RJD can be an effective tool for production enhancement and completions for both new wells and workover wells with radials up to 1,000 ft (305 m) long. It is a very viable, cost effective alternative for fracturing in marginal fields. However, candidate selection is a crucial parameter in RJD success. Petrophysical studies, *in situ* stress magnitude/distribution and rock cutting mechanics are necessary before well intervention to maximize benefits from RJD. In addition, further investigation is recommended to overcome RJD limitations and to explore new applications.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

Nomenclature

A_i = Nozzle area
A_o = Hose inner area
C = Jet bit discharge coefficient
d_h = Inner diameter of flexible hose
d_i = Inner diameter of coiled or straight tubing
d_o = Outer diameter of coiled tubing
f = Well friction coefficient
F_{df} = Friction force between wellbore and deflector
f_f = Friction factor
F_f = Friction force of well to high-pressure hose
F_j = Ejecting force generated by fluid jetting from nozzles

$F_{p\text{-}out}$ = Fluids pressure on the forward surface of jet nozzle

F_{pull} = Pulling force of the high-pressure hose and the jet bit

g = Gravitational acceleration

l_h = Length of the high-pressure hose

l_t = Length of the coiled tubing section or straight tubing section

P_{out} = Ambient fluid pressure around the jet bit

Q = Flow rate

v = Fluid velocity in coiled or straight tubing

v_i = Fluid velocity in the nozzle

v_o = Fluid velocity in the hose

α = Correlation coefficient of deflector resistance

ΔP_{bit} = Pressure loss through bit nozzles

ΔP_{CT} = Friction pressure loss in coiled tubing

ΔP_{hose} = Friction pressure loss in flexible hose

ΔP_{pump} = Total pump pressure

ΔP_{ST} = Friction pressure loss in straight tubing

μ = Fluid viscosity

ρ = Fluid Density

ρ_h = Weight of high-pressure hose per meter

φ = Angle of the nozzle

Acronyms

CT = Coiled tubing
FOI = Fold of increase
mD = milli-Darcy
BOPD = Barrel oil per day

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