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Plasma Pulse Technology: An uprising EOR technique

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ABSTRACT

Conventionally oil recovery factor is too low, which leaves great prospects for the application of enhanced oil recovery (EOR) methods to increase recovery factor. EOR methods are capital intensive and few are environmentally hazardous. So the paper discusses on the alternate enhanced oil recovery technique which has tremendous potential to curb the challenges of conventional EOR methods. Plasma pulse technology (PPT) aided EOR treatment is administered with an electric wireline conveyed plasma pulse generator tool that is run in the well and positioned alongside the perforations. Using energy stored in the generator's capacitors, a plasma arc is created that emits a tremendous amount of heat and pressure for a fraction of a second. This in turn creates a broad band of hydraulic impulse acoustic waves that are powerful enough to clean perforations and near wellbore damage. These waves continue to resonate deep into the reservoir, exciting the fluid molecules and increasing the reservoirs natural resonance to the degree that it can break larger hydrocarbon molecules to smaller one and simultaneously reducing adhesion tension which results in increased mobility of hydrocarbons. The plasma pulse technology has been successfully used on production as well as injection wells. It has been used often as a remedial procedure to increase well's productivity that has been on production for a period of time. This paper throws light on fundamentals of this advancing plasma pulse technology, contrasting it with recent EOR techniques. Effectiveness of treatment in increasing oil recovery, it's applicability to different reservoir types and results achieved so far are also covered in the paper.

1. Introduction

The main reason for "being so wrong" about oil's future availability is the over-reliance on analytical techniques that fail to appreciate petroleum as an economic commodity powered by the constant advance of technology. There is no approximate date of "running out of oil" since there are a lot of factors to take into consideration when it comes to estimating the reserves. By general definition of reserves, they are the discovered accumulations of hydrocarbon which can be legally, economically and technically extractable. It has been observed that prediction models on peak oil production (including Hubbert's theory) do not stand with increasing giant field discoveries adding on to total world reserves. Any forecasts can be done on basis of future production profile, consumption rates and implied ultimate recoverable reserves. All the parameters into consideration are highly variable, so prediction or approximation of running out of oil is very sensitive subject to assumptions considered and still it has extremely high chance of variation (Sorrell et al., 2010). Most important factors that define reserves are: economics and technology. For example, considering a field with recovery factor of 30%, other 70% is not economically profitable or technologically not possible to recover. So when a field is abandoned, there is still a lot of oil that can be recovered with more investment and advanced technology. And we have no estimate on how far these two factors can take us in future. Average worldwide recovery factor of conventional oil reserves is somewhere in between 20 and 40% (Muggeridge et al., 2014), although this number is an inference rather than anything particularly evidence-based. Recovery factor can even be as high as 80% depending on type of reservoir, drive mechanism, crude properties technological development and economical investments (Thakur and Rajput, 2011). As graphically summarized in Fig. 1, secondary recovery takes the recovery factor in between 30 and 50% and tertiary or enhanced oil recovery methods raises the number varyingly in range of 50–80% depending on type of method used and reservoir characteristics and compatibility with that method can increase the factor significantly (Stosur et al., 2003). But still for unconventional and horizontal wells, effective EOR technology has

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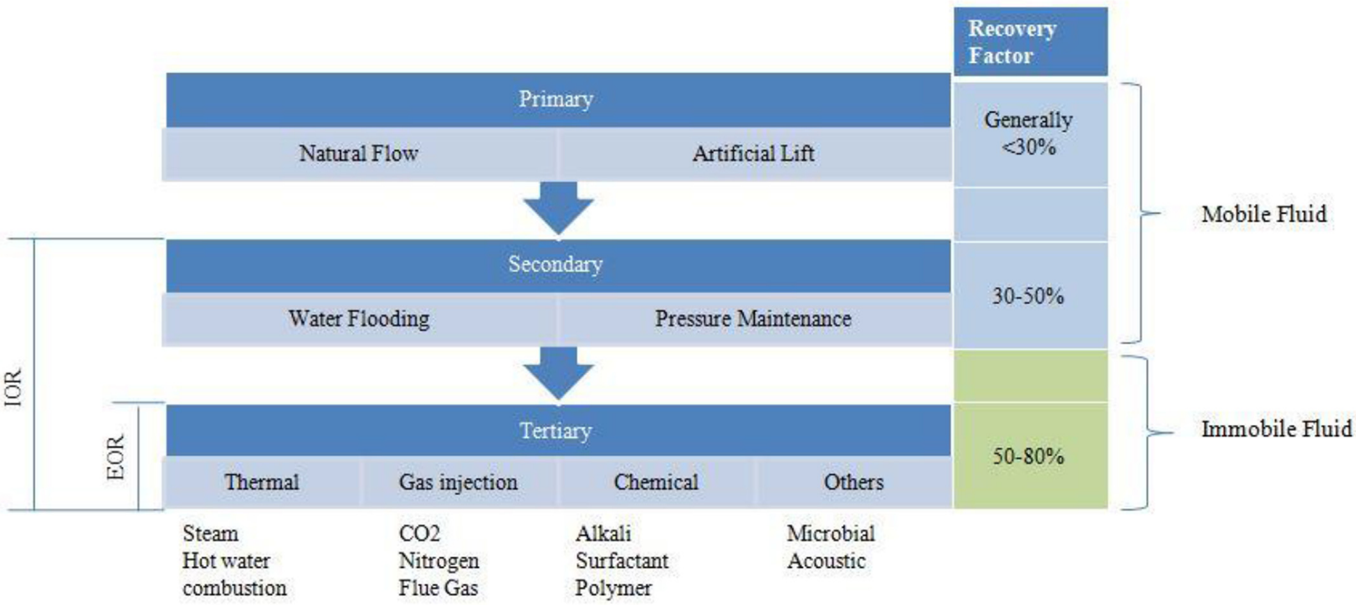

Fig. 1. Defining improved oil recovery (IOR) and enhanced oil recovery (EOR) (Stosur et al., 2003).

still not been devised (Goswami et al., 2017). Because if the injection well is vertical, then the effective area will be very small (i.e. the size of well bore diameter) for the displaced/swept hydrocarbon to be produced in case of gas injection, chemical flooding, steam injection or other flooding EOR methods as shown in Fig. 2. Moreover, movement of subsurface fluid because of injection well will be perpendicular to the movement of fluid caused due to drainage by production well. This may lead to displace the fluid parallel to well bore instead of their movement towards the well bore. Hence, the flooding EOR methods are relatively ineffective in horizontal wells as compared to vertical wells. While PPT will make it possible to uniformly decolmatate the entire producing interval of the horizontal well without large expense and time allowing drainage of more reservoir fluids.

Thus, the recovery factor leaves vast target for the enhanced oil recovery (EOR) techniques. The EOR techniques was played and are playing as of now their liable role in increasing the recovery factor. Some most commonly used forms of EOR include water or gas injection, thermal techniques or chemical flooding. These involve injecting water, gas, steam or chemicals to flush or sweep the residual oil from the reservoir. The primary challenge faced in EOR technologies is the high injection cost which makes it capital and resource intensive, and expensive (Muggeridge et al., 2014). While EOR technologies have grown over the years, significant challenges remain. As an alternative to this costly methods, the plasma pulse technology is thriving its foot into EOR sector as upcoming technology that requires minimum capital investment, is environmentally safe and does not involve use of any chemicals or water.

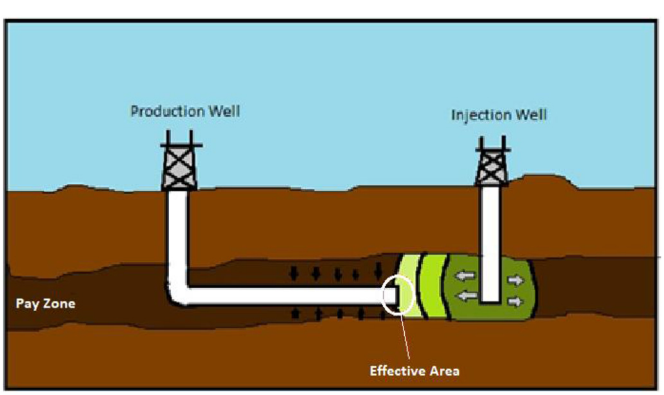

Fig. 2. Illustrative diagram showing EOR treatment being applied to horizontal well and ineffectiveness of EOR method due small effective area of producing well being treated.

All these factors along with security for future energy demands, there are need to develop economically feasible technologies that aid to increase in production and can be competent with low oil rates where most EOR techniques are found immoderate. With regards to this, introduction of plasma pulse technology (PPT) is found enhancement over traditional EOR techniques in terms of not only cost of applying it on the fields but also reduction in environmental damage as there is no use of chemicals. Moreover, application of the technique does not found use of heavy mechanical accessories for its implementation and it also serves the purpose as well stimulation tool.

The paper discusses the glimpse of traditional EOR methods and their comparative study with the plasma pulse technology, its detailed working, tool specifications and results so far achieved. It highlights the principle of the technology by comparing it through novel illustrations. Effect of PPT on crude property like viscosity is presented. Along with being an EOR technique, this method serves the purpose of stimulation of near well bore region. Scope of the treatment in EOR sector by synergy with conventional EOR methods is highlighted along with the limitations on application of the plasma pulse treatment. Effectiveness of the PPT in terms of principle behind it results on production and injection wells, different type of reservoir formation, cost effectiveness and environment considerations is highlighted in this paper.

2. Conventional EOR processes

Various EOR methods have been categorized mainly into four major groups which are as shown in Fig. 3 (Abramova et al., 2014).

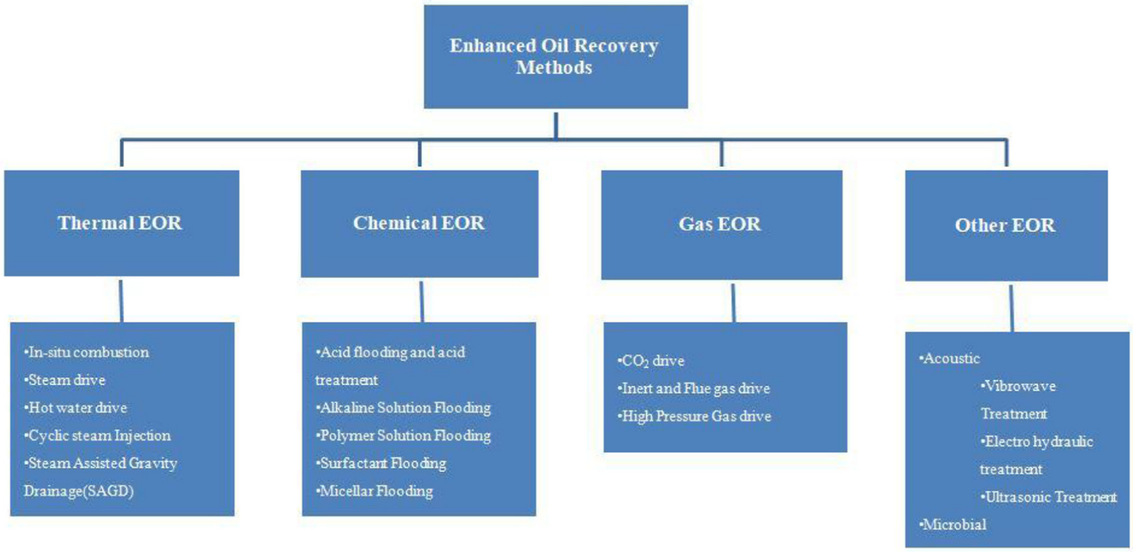

Fig. 3. Conventional EOR classification and its type (modified after Abramova et al., 2014).

Thermal EOR is carried with an intention of fundamental changes in physical and chemical parameters of oil. In this approach, various methods are used to heat the crude in-situ to reduce its viscosity and thus reduce mobility ratio (M) (*where* $M = \lambda_w/\lambda_o$). The method is related to change properties of oil rather than that of the reservoir as such in hydraulic fracturing (increasing or creating artificial permeability). In case of thermal EOR 30–58% of oil can be recovered (Abramova et al., 2014; Santos et al., 2014). Recovery factor of oil for different thermal EOR varies and also varies depending on the type and heterogeneity of formation. Typically, recovery factor for cyclic steam injection is 10–30% (Alvarez and Han, 2013) and that of steam flooding and SAGD is 40–60% (Harrigal and Clayton, 1992; Jiang et al., 2010).

Gas injection or miscible flooding is most commonly used EOR at present time. Miscible flooding is a term used for injection process of introducing miscible gas into reservoir so as to reduce the interfacial tension between oil and water resulting in improved oil displacement (Fath and Pouranfard, 2014). Gases in this procedure include CO_2, nitrogen or natural gas. Gas methods enable to increase the production of oil by 5–19% more compared to ordinary flooding applied during secondary recovery (Davarpanah, 2016).

Chemical methods of EOR are based on injecting chemical reagents or their mixtures with water into the reservoir through injection or production wells in order to clean the wellbore perforation zone like matrix acidization or to increase sweep efficiency of displacing fluids.

Surfactants/polymers are used with an aim to change interfacial tension and surface tension reducing viscosity and increasing mobility of oil with respect to water and hence increasing recovery. Up to 35% of the reserves can be recovered using chemical EOR processes (Mandal, 2015; Raffa et al., 2016).

Geophysical methods of EOR are developing over the last few years. Their market share is still low compared to the share of the methods described above, but grows constantly. In case of physical EOR instead of matter (hot water, steam, gas, chemicals, etc.) physical (or geophysical) fields are used to affect the reservoir. The nature of these fields can be different: from electromagnetic to acoustical (Abramova et al., 2014). Though they are non-invasive and might be less expensive as no need for separate injection well, still very less information is available about these methods and satisfactory results are yet not obtained.

3. Plasma pulse technology on oil recovery enhancement

It was first introduced to the U.S. industry in 2013. The technology was invented at St. Petersburg State Mining University in Russia. Instead of using the method of hydro fracturing where pressurize fluids are used to open the channels or to create the channel and induce artificial permeability, the plasma pulse technology produces high energy plasma arc which generates tremendous energy in form of heat and acoustic waves for a fraction of second. Subsequently, this impulse waves created removes any clogged sedimentation from the perforation zone, i.e. scale, fines, drilling mud, etc. Along with this, the service may lead up to forming nano- to micro-scale fractures as the series of impulse waves penetrate deep into the reservoir resulting in enhancement of permeability (Ageev and Molchanov, 2015). Oil can then flow more easily from the reservoir into the well and be pumped to the surface. The end result is an increase in sustained production which can last for as long as a year.

The invention of technology is directed to a plasma source for generating nonlinear, wide-band, periodic, directed, elastic oscillations (Ageev and Molchanov, 2015). Working of the plasma source tool is discussed later in this paper. PPT is mainly deployed for stimulating wells and deposits through controlled, periodic oscillations. The principle behind the invention of the technology can be considered as the results obtained in well productivity in wells affected by natural seismic phenomenon like earthquakes (Paiamana and Nourani, 2012). Though it is also noted that earthquakes result into deteriorating of well productivity in most cases, but close look on the phenomenon shows that effect of seismic wave on reservoir decreases or some time increases the productivity depending on the type of formation, but effect of these waves on hydrocarbon fluid results in oscillation of molecules at their resonance frequency and helps in reducing surface tension and also increases oil mobility by breaking of larger globules into smaller globules and if weak bonds are prevailing than results into smaller hydrocarbon chains also. P-waves generated during earthquake were found to clean the near wellbore region and one such demonstration was found in gas field of Iran where condensate formed was cleaned up due to earthquake resulting in increased productivity (Paiamana and Nourani, 2012). The example similar to this can be thought of opera singer breaking the glass by resonating

Fig. 4. Effect of PPT on the cement integrity after and before its application.[1]

the glass molecules with acoustic (i.e. sound) waves only. Similarly, shock wave is emitted from the metallic plasma created in the electrode gap. The shock wave is directed from the metallic plasma into the fluid medium and as a result nonlinear, wide-band, periodic and elastic oscillations are generated in the fluid medium. These controlled shock waves are concentrated and focused into particular zone of perforation, reducing its ill-effect to other strata if any. The pressure waves/shock waves generated have no effect on the bonding of cement. The cement has been set firmly with casing and formation and hence it is not allowed to oscillate, acting as solid non porous body just like steel. As the cement particles are not allowed to oscillate, ill effect of pressure pulse/waves on cement integrity would not be seen and evidence of the same is as illustrated in Fig. 4.

The method is performed excluding the use of chemicals that are harmful to humans or the environment. The nonlinear, wide-band, periodic and elastic oscillations preferably have a frequency ranging from 1 Hz to 20 kHz (Ageev and Molchanov, 2015). The elastic oscillations preferably have a short pulse of approximately fifty to fifty-five microseconds and propagate through the fluid medium at low velocities (Ageev and Molchanov, 2015). PPT can be used for treating production, injection, mature, depleted, land, onshore, or offshore wells/boreholes/openings. Application of this method results in the emergence of long-lasting resonance features, improving the permeability of the porous media, increasing the mobility of fluids in the well and surrounding media, and improving the well production/injection capacity and hydrocarbon recovery.

4. Technical specifications of the PPT tools

Plasma pulse tool houses two electrodes and the electrodes define electrode gap across which plasma arc is generated. The first electrode (above electrode) is preferably a high voltage electrode and is coated or fusion bonded with a high melting point, refractory metal or alloy. Preferably, the first electrode is electrically insulated from the plasma emitter and the second electrode is electrically grounded to the plasma emitter (Ageev and Molchanov, 2015). The tool further houses electronic and relay blocks connected with transformers and capacitors. Transformers (Step-Up Transformer) increases the voltage of input signal (AC current) to many folds. Capacitors, following the law of $Q = CV$ stores more number of electric charges corresponding to increased voltage. Electrical charges hence stored in capacitors are discharged in a fraction of seconds creating plasma arc across two electrodes. Simplified circuit is shown in Fig. 5. The system also includes a support cable having a fixed end physically connected to a mobile station and a remote end physically and electrically connected to the plasma source same as in well logging services or as that of perforation gun. The support cable is configured to be deployed into well conditions.

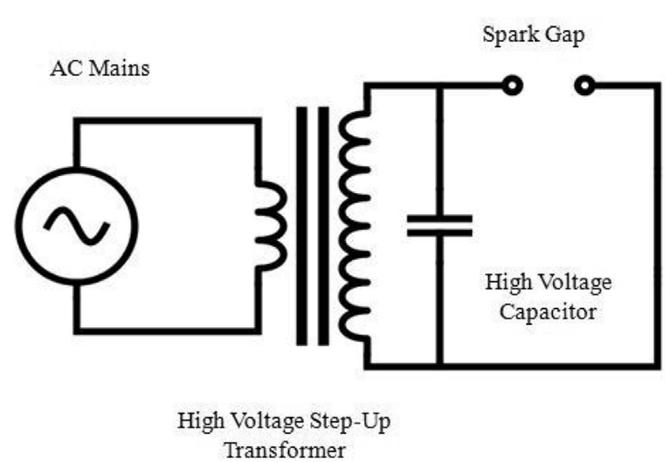

Fig. 5. Simple electric circuit diagram showing formation of plasma arc across spark plug.

[1] http://www.novasenergy.ca/technology/presentations.html.

A ground control unit is mounted on the mobile station and electrically connected to the fixed end of the support cable. Well is shut-in prior to application of PPT job. PPT tool is lowered in the well via monocable with help of winch van and placed in front of perforated zone. Tool is oriented in specific direction and plasma arc is generated with electric signal from surface unit.

The ground control unit has a recording block configured to record and store data about the oscillations. The ground control unit of the apparatus may be provided with an electronic voltage stabilizer and power supply with a toroidal transformer having an incremental adjustment of output voltage (Ageev and Molchanov, 2015). The ground control unit is preferably modular with parts and PCBs provided with interchangeable connectors and may be powered by an AC or DC electrical line by using generator, solar, tidal or wind power supply with voltage up to 300 V. There is provision in the truck to record/store data, including: date, time, operation duration and the number of pulses executed in the process of well treatment and signals to sensors installed on the plasma source and data from the sensors. The plasma source has generally cylindrical body as other logging tools providing resistant to impact. There are numerous ways to describe wave propagation in a porous medium, including Biot's low-frequency equations (Corapcioglu and Tuncay, 1996). The rate of propagation of the disturbance in an elastic porous medium saturated with fluid is characterized by the piezo conductivity coefficient, which depends on the porous medium structure, for example, the diameter of the pores and the elastic modulus of a productive deposit. Accordingly the frequency, wave band and oscillations are calculated and controlled with voltage control and changing the gap between electrodes as per requirement. The plasma source of wide-band, periodic, directed, elastic oscillations is nonlinear as the enough energy is released from that stored in capacitors in brief period of time in limited volume which accompanies increase in temperature by 28,000 °C and high pressure shock wave exceeding pressure 550 MPa (Ageev and Molchanov, 2015). Other specifications of the tools are as mentioned in Table 1 (Ageev and Molchanov, 2015).

Simplified circuit of plasma pulse technology:

(1) Input AC current of low volt
(2) Voltage increased by step-up transformer
(3) Energy in form of electric charge gets stored in capacitor
(4) Sudden discharge occurs across spark gap by discharging of capacitor generating shock wave and heat nearby to the spark gap

This is simplified circuit, but in reality it is very complex with relays, PCBs and controllers for preventing back current, for earthing remaining charges across the capacitor and for calculated and controlled formation of sparks across the gap.

5. Results

Every technology is developed on the basis of the principle theory supporting its applications and its difference from existing technologies. Supporting theories are considered speculations until and unless the technology has been experimented and satisfactory results are obtained. PPT has been successfully implemented over 200 wells around the world and the success is precedent with over 500% improved production in some wells lasting the effect for 5–6 months on an average. A very few number of wells have reported problems. Cost of treatment on well is minimized as only 155 pound tool has to be lowered without requirement of any heavy workover rigs or surface facilities.

5.1. Effect of PPT on viscosity of oil

The aim of improving oil recovery by reducing effective viscosity is achieved by experimenting PPT on the heavy oil sample, and results for the same are shown in Fig. 6.

Experimental stand was devised to investigate results of plasma pulse action on rheology of crude oil. Samples in the experiment were subjected to 10–40 pulses within the frequency range of 0.1–10 Hz (Maksyutin and Khusainov, 2014). Reduction in oil viscosities up to 30% depending on the type of crude oil was observed during the experiment. It was found that reduction in effective viscosity of crude samples was result of thixotropic structure destruction. Depending on the composition of crude, their molecular structures can be excited with particular range of frequency. To identify the resonant frequency of any oil sample can be the scope of future research work.

But the result of experiment mentioned above doesn't take into account the formation/rock properties. So to support the effectiveness of the technology, few of real field data (of Russian oil fields) comparing the oil production before and after application of PPT has been brought up in Fig. 7. Furthermore, the considerable influence of PPT on the injection wells is being statistically explained in Table 2.

5.2. Effect of PPT on production well

Results of plasma pulse on few of Russian oil fields show remarkable increment in oil production after the treatment simultaneously leading in lower water cut thereafter. But in some cases water cut is observed increasing after treatment or remains nearly same. So it is more appropriate to state that the plasma pulse action results in increasing total fluid production with increment in oil production (in almost every case) irrespective of increased or decreased water cut. Due to unavailability of reservoir formation knowledge, effectiveness of the treatment on different formation like sandstone and limestone cannot be commented. But still the effectiveness of PPT treatment can be visualized with increasing oil production by reduction in oil viscosity and increment in total fluids produced.

But for any EOR application project, the extent of effectiveness on various formations plays a lead role in decision-making process and ultimately the economics of the overall project. Results of PPT on following few US wells will give insight to the extent of effectiveness of treatment on sandstone and limestone reservoirs (most

Table 1
Specification of plasma pulse tool (Ageev and Molchanov, 2015).

Tool attributes	Specifications
Tool diameter	3.5 inch
Length	~8 ft
Weight	155 pounds (~70 kg)
Capacitor's charging voltage	2.5–6 kV
Pulse power	1.5–2 kJ
Number of pulses	2000 (Electrodes needs to be changed afterwards)

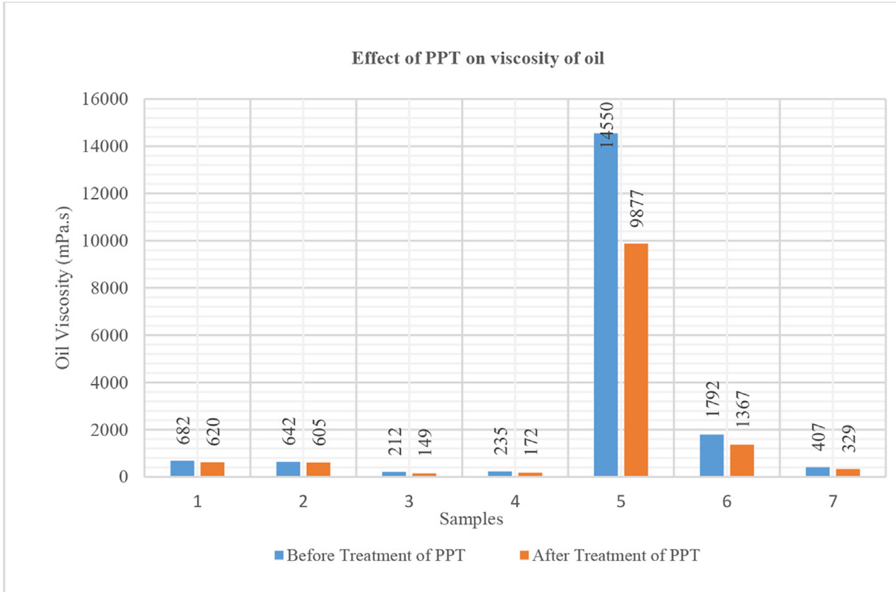

Fig. 6. Reduction in effective viscosity observed after application of PPT (modified after Maksyutin and Khusainov, 2014).

commonly found reservoir rocks). Fig. 8 clearly shows the increment in oil production in sandstone reservoirs is astonishing as compared to limestone reservoirs. Even though, limestone formations also show increment in oil production.

Not only percentage increase plays the major role, but ultimate BOPD after treatment is what matters in deciding the undertaking of treatment. As for example (from Fig. 8) 200% increment in Mississippi Limestone of Kay County Oklahoma will serve the profit as compared to 267% increment in Red Fork sandstone formation of Creek County, Oklahoma. Extent of success of the technology also depends on various other parameters like reservoir heterogeneity, permeability, WOR, subsurface temperature, etc which eventually leads to effectiveness of treatment. But consideration of these parameters needs extensive modelling approach which is out of scope of this paper.

5.3. Effect of PPT on injection well

Not only production wells, but treatment has been proved equivalently effective in injection wells as it can be concluded from Table 2. As the main purpose of near well bore cleaning is effectively being served by the treatment which results not only in improved reservoir deliverability but also improved reservoir intake which is necessary for many other EOR applications like polymer/surfactant flooding, gas injection or water alternate gas injection (WAG) processes.

6. Discussion

After having the knowledge of principle behind the plasma pulse technique, working of plasma pulse tool, its specifications and field tested results; this section of paper discusses the plasma pulse EOR technique in comparison with other conventional EOR methods and also the conditions which support or enhances the effect of treatment.

Gas injection, especially CO_2, is a popular EOR method and is applicable to light oil reservoirs of both sandstone and carbonate (Alagorni et al., 2015). It is highly popular because of two reasons, oil productivity is increased and also a greenhouse gas is disposed in the process which helps the environment greatly. The success of this EOR method depends on successful availability of low-cost natural CO_2 from nearby areas. The current challenges for the gas injection EOR are gravity segregation and most importantly availability of low-cost gas.

Chemical EOR faces significant challenges especially in light oil reservoirs. The reason is lack of compatibility of chemicals in high temperature, pressure and salinity environments (Pal et al., 2017). Enhanced oil recovery pumps large quantity of brine to the subsurface and again back to the surface. The brine is toxic and contains radioactive substances and heavy metals. Intrusion of this to aquifer may degrade the quality of useful water or may damage soil fertility if not managed/discharged properly.

Thermal EOR is a complex process, requiring large capital investment, is difficult to control and was one of the oldest amongst traditional EOR methods. Though thermal EOR is proved quite effective for sandstone reservoirs there are many problems related to different techniques of thermal EOR. Few of them are as following (Lyons, 1996):

(1) Produced flue gases can present environmental problems
(2) Operational problems such as severe corrosion caused by low pH hot water, serious oil-water emulsions, increased sand production, and pipe failures in the producing wells as a result of the very high temperatures
(3) Steam flooding is not normally used in carbonate reservoirs.
(4) Adverse mobility ratio and channeling of steam

In comparison to these traditional methods, the plasma pulse technology has been proved positive in mitigating the limitations of further mentioned EOR technique. PPT not uses any chemicals for conducting operation; there is no need of any gases in whole process neither the gas is being used for creating plasma in the PPT tool. It can be lowered in the production well itself. There is no need of injecting well unlike other EOR methods. Operation can be easily carried out by lowering tool with the help of mono cable by truck analogous to well logging services. Wells can be put into production in very short time after the operation. Application of plasma pulse treatment is also shown positive effect on nearby wells up to

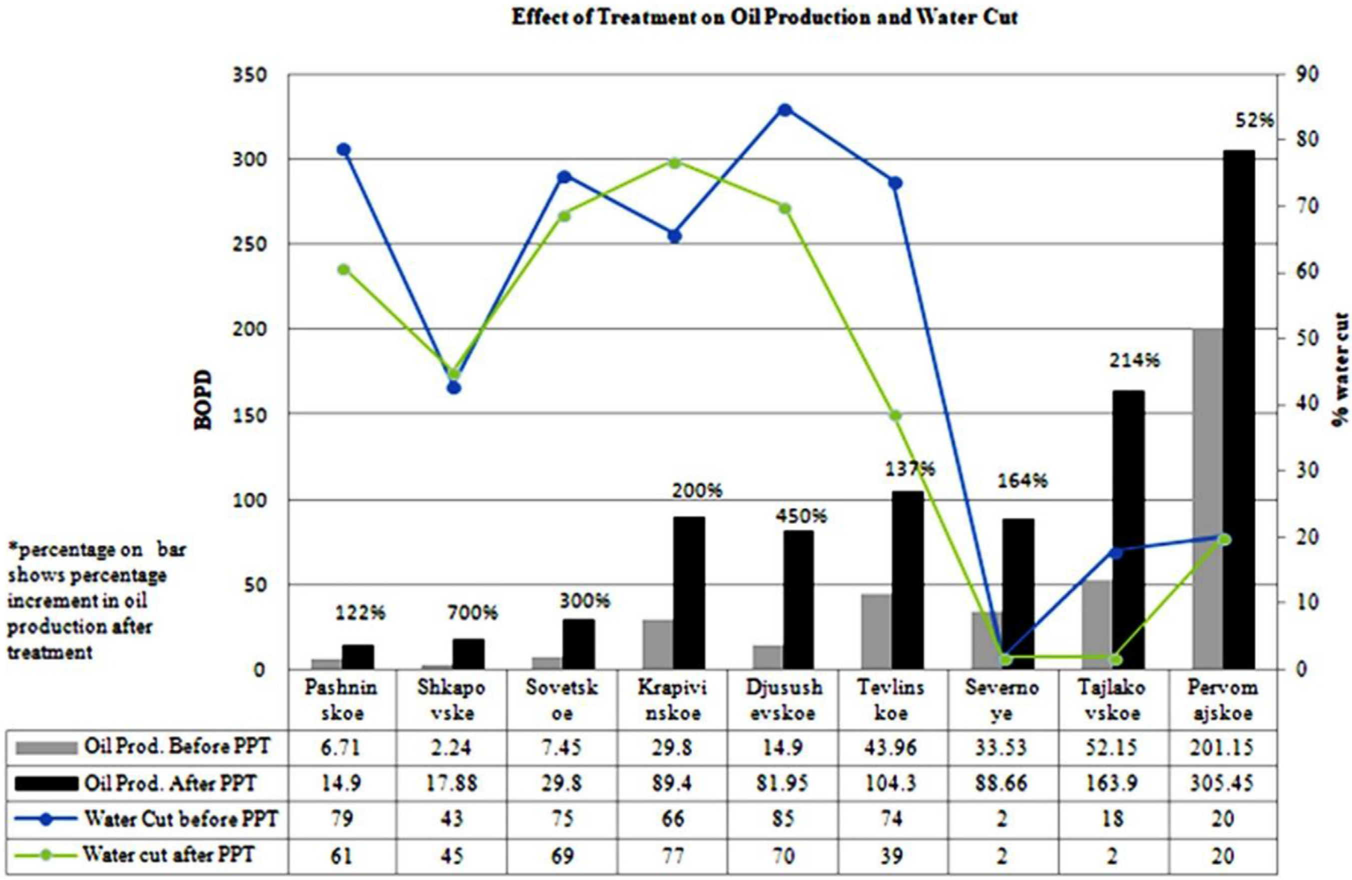

Fig. 7. Oil production and % water cut before and after of PPT treatment on production well of few oil fields of Russia (data from Novas Energy, 2015).[2]

Table 2
Before and after effect of PPT on injection well of few oil fields of Russia (Novas Energy, 2015).[3]

Oil fields	Bbls/day (Before)	Bbls/day (After)	%increase
Lomovoe	119	728	511
Poludennoe	314	942	200
Sutorminskoe	157	1080	588
Tajlakovskoe	31	376	1100
Arlanskoe	31	138	340
Turchaninovskoe	125	546	335
Muravlenskovkoe	1727	4396	155

~400 m distance and is expected to have effect on reservoir up to radius of 1 km (Chellappan et al., 2015).

Though the plasma pulse technology aims to alleviate few of the drawbacks of conventional EOR methods, the technology is neither alternative to these conventional EOR methods nor it replaces the need of hydraulic fracturing. It is the technique which mainly aims in cleaning the near well bore region to clear the pathway for oil to flow fast. But simultaneously it provides resonant oscillations to fluids which results into decreasing viscosity and decrease in interfacial tension with that of formation rock (Maksyutin et al., 2014). Moreover, sudden impulse also causes enhancement in micro fractures or widening of pre-existing micro fractures which leads in decreasing capillary pressure which allow the residual oil to flow with that of mobile reservoir fluids. While producing for long time, reservoirs fluids carry solids/sediments along with them which eventually end up in clogging pore spaces providing restrictions to flow. This is the time when plasma pulse treatment should be done on the well. This method does not provide the push to immobile oil for flowing towards well bore. Hence it cannot replace the need of various flooding EOR methods. But use of plasma pulse in conjunction with conventional EOR can definitely improvise the effect and result of conventional EOR technique. Current oil field problems associated with optimum recovery are heavy crude in formation, obstruction to fluid flow, higher water cut, residual oil in isolated or dead end pores, high interfacial tension and surface tension between fluids and formations, poor pore connectivity, etc. The plasma pulse treatment contributes directly or indirectly, and up to lesser or greater extent in mitigating these problems.

From the result section it can be deduced that the efficacy of the plasma pulse treatment on sandstone reservoir is higher than that of limestone reservoirs. The reason may be, the treatment efficiently removes clogging/obstructions in the fluid flow in case of sandstone, and as sandstone are clastic sedimentary rocks, it have inherent better permeability as related to limestone. So all what is needed is, opening the way up for fluid to flow. Clogging is the process due to solid deposition, wax deposition, salt formations, etc. and the frequency with which it may happen depends on formation type, fluid properties, and subsurface conditions. Limestone is a chemical sedimentary rock with poor permeability for the same porosity as that of sandstone. Hence the treatment on limestone might be creating additional nano- to micro-scale fractures but due

[2] http://www.novasenergy.ca/technology/presentations.html.
[3] http://www.novasenergy.ca/technology/presentations.html.

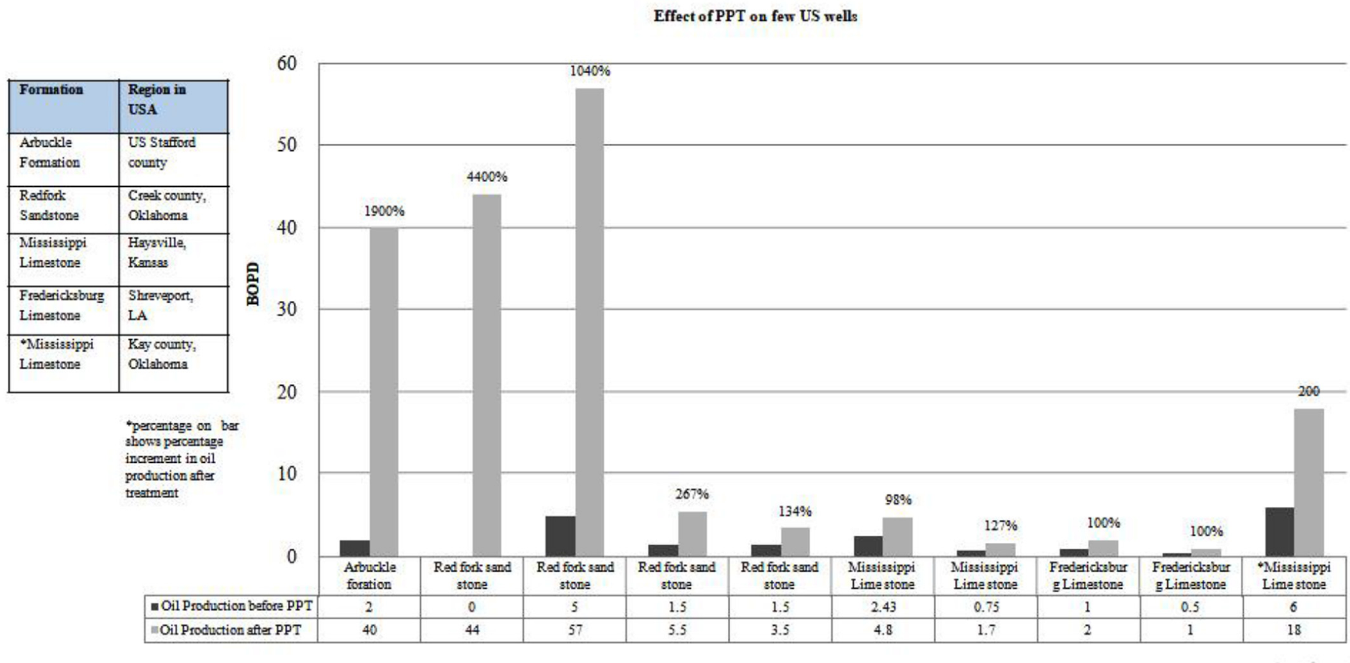

Fig. 8. Effect of PPT on oil production from sandstone and limestone formations of few US fields.[4]

to lack of connectivity and also due to nature of dissolution and reprecipitation, it ultimately results in not so remarkable effect of treatment on such formations.

As with leverage of each technology, it has limitations and so is with the application of the plasma pulse treatment. The treatment is better suited for coarse grained, consolidated sandstone reservoirs. Crude with wax deposition problems may lead in clogging frequently and it is not economically feasible to apply treatment within short span of time. Resonant frequencies of reservoir fluids shall be thoroughly studied and frequency along with intensity of pulses shall be modelled accordingly. Reservoir fluids with higher sand production may clog the matrix very often, so it is economically unviable to apply plasma pulse treatment time and again. So it can be inferred that this technology is better suited for consolidated sandstone formation.

7. Conclusion

Low crude price and increasing demand have put forward a great challenge to the E&P sector of oil and gas industry to develop and deploy the technology that is cost-effective and (technically more) efficient at the same time. From the initial results of the plasma pulse technology, it has been found that the technology is not only effective in terms of enhancing oil recovery but also cost-effective along with environment-friendly. Success of the plasma pulse treatment on particular well and formation depends on type, composition and rheological properties of crude oil and properties of reservoir. Formulation of optimum frequency range (resonant frequency) depending on different type of crude oil and maximum number of pulses for better depth of penetration can lead to maximize the chances of success and greatly improves the results. The synergy between this technology and that of conventional EOR technologies will mitigate the limitations of each of them emerging as a revolutionary step in EOR sector. This advanced technology will soon find its widespread market in upcoming future as effective, easily deployable and economically viable enhanced oil recovery technique.

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References

Abramova, A.V., Abramov, V.O., Kuleshov, S.P., Timashev, E.O., 2014. Analysis of the modern methods for enhanced oil recovery. In: Umesh, C.S., Sivakumar, Sri, Ram, P. (Eds.), Energy Science and Technology, Oil and Natural Gas, vol. 3. Studium Press LLC, USA, pp. 118–148.

Ageev, P.G., Molchanov, A.A., 2015. Plasma source for generating nonlinear, wide-band, periodic, directed elastic oscillations and a system and method for stimulating wells, deposits and boreholes using the plasma source. US Patent No., US 9,181,788 B2, 10 Nov. 2015.

Alagorni, A.H., Yaacob, Z.B., Nour, A.H., 2015. An overview of oil production stages: enhanced oil recovery techniques and nitrogen injection. Int. J. Env. Sci. Dev. 6 (9), 693–701.

Alvarez, J., Han, S., 2013. Current overview of cyclic steam injection process. J. Pet. Sci. Res. 2 (3), 116–127.

Chellappan, S.K., Al Enezi, F., Marafie, H.A., Bibi, A.H., Eremenko, V.B., 2015. First Application of Plasma Technology in KOC to Improve Well's Productivity. Society of Petroleum Engineers, Tulsa.

Corapcioglu, M.Y., Tuncay, K., 1996. Propagation of waves in porous media. In: Corapcioglu, M.Y. (Ed.), Advances in Porous Media, vol. 3. Elsevier, Netherlands, pp. 361–440.

Davarpanah, A., 2016. Evaluation of gas injection in the horizontal wells and optimizing oil recovery factor by eclipse software. J. Chromatogr. Sep. Tech. 7 (6), 1–4.

Fath, A.H., Pouranfard, A.R., 2014. Evaluation of miscible and immiscible CO_2 injection in one of the Iranian oil fields. Egy. J. Pet. 23 (3), 255–270.

Goswami, R., Kumar, R.S., Narukulla, R., Sharma, T., 2017. Feasibility of plasma pulse technology in enhancing productivity of the oil fields of Barmer, Rajasthan basin, India. In: International Conference on Challenges and Prospects of Petroleum Production and Processing Industries. IIT (ISM), Dhanbad, pp. 1–7.

Harrigal, R.L., Clayton, C.A., 1992. Comparison of Conventional Cyclic Steaming and Steam Flooding in a Massive, Dipping, Midway Sunset Field Reservoir. Society of Petroleum Engineers, Tulsa.

[4] http://www.jardineoil.com/case-studies .

Jiang, Q., Thornton, B., Houston, J.R., Spence, S., 2010. Review of thermal recovery technologies for the Clearwater and Lower Grand Rapids formations in the cold lake area in Alberta. J. Can. Pet. Tech. 49 (09), 2–13.
Lyons, W.C., 1996. Reservoir engineering. In: Lyons, W.C. (Ed.), Standard Handbook of Petroleum and Natural Gas Engineering, vol. 2. Gulf Professional Publishing, Houston, pp. 3–362.
Maksyutin, A.V., Khusainov, R.R., 2014. Results of experimental researches of plasma pulse action technology for stimulation on the heavy oil field. World App. Sci. J. 31 (2), 277–280.
Maksyutin, A.V., Khusainov, R.R., Rogachev, M.K., Tananykhin, D.S., 2014. Laboratory studies of the exposure to the diffusion process with simultaneous application of nonionogenic surfactants and plasma-impulse technology. Life Sci. J. 11 (6s), 276–279.
Mandal, A., 2015. Chemical flood enhanced oil recovery: a review. Int. J. Oil Gas. Coal Tech. 9 (3), 241–264.
Muggeridge, A., Cockin, A., Webb, K., Frampton, H., Collins, I., Moulds, T., Salino, P., 2014. Recovery rates, enhanced oil recovery and technological limits. Phil. Trans. R. Soc. A Math. Phys. Eng. Sci. 372, 1–25.
Paiamana, A.M., Nourani, M., 2012. Positive effect of earthquake waves on well productivity: case study: Iranian carbonate gas condensate reservoir. Sci. Iran. 19 (6), 1601–1607.
Pal, S., Mushtaq, M., Banat, F., Al Sumaiti, A.M., 2017. Review of surfactant-assisted chemical enhanced oil recovery for carbonate reservoirs: challenges and future perspectives. Pet. Sci. 15 (1), 77–102.
Raffa, P., Broekhuis, A.A., Picchioni, F., 2016. Polymeric surfactant for enhanced oil recovery: a review. J. Pet. Sci. Eng. 145, 723–733.
Santos, R.G., Loh, W., Bannwart, A.C., Trevisan, O.V., 2014. An overview of heavy oil properties and its recovery and transportation methods. Braz. J. Chem. Eng. 31 (03), 571–590.
Sorrell, S., Miller, R., Bentley, R., Speirs, J., 2010. Oil futures: a comparison of global supply forecasts. Ene. Pol. 38 (9), 4990–5003.
Stosur, G.J., Hite, J.R., Carnahan, N.F., Miller, K., 2003. The Alphabet Soup of IOR, EOR and AOR: Effective Communication Requires a Definition of Terms. Society of Petroleum Engineers, Tulsa, pp. 1–3.
Thakur, N.K., Rajput, S., 2011. World's oil and natural gas scenario. In: Thakur, N.K., Rajput, S. (Eds.), Exploration of Gas Hydrates- Geophysical Techniques. Springer Berlin Heidelberg, Berlin, pp. 29–47.

Web References

http://www.novasenergy.ca/technology/presentations.html, 2015, (8th May, 2018).
http://www.jardineoil.com/case-studies (8th May, 2018).