

# An Investigation of the Effects of Charged Polyacrylamide Injection on Asphaltene Deposition in Porous Media

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## ABSTRACT

This study has investigated the effects of three different polar polyacrylamides (anionic, cationic, and nonionic) on asphaltene deposition in porous media. All experiments were carried out in various dead oil flow rates (0.2, 0.1 and 0.02 cc/min) and different polymer concentrations (500, 2500, 4000 ppm). Results indicated that asphaltene precipitation was affected by the presence of polar additives such as charged polyacrylamide. In general, anionic polyacrylamide increased the asphaltene deposition. The amount of deposition was directly proportional to the increasing concentration of anionic polyacrylamide. Anionic polyacrylamide with the concentrations of 2500 and 4000ppm behaved as a promoter while the hydrophilic property of nonionic polyacrylamide acted as an inhibitor of the precipitation. Stabilization of asphaltene deposition was disturbed in the presence of cationic polyacrylamide. Moreover, the electrostatic and acid-based mechanisms showed a retarding effect. The flow rate is another parameter, which is taken into account besides other factors.

## 1. Introduction

Asphaltenes constitute chemically heterogeneous organic molecules in crude oil that possess high degree of aromaticity, polarity, and have a tendency to form supermolecular aggregates in solution [1]. Pipeline fouling due to the deposition of asphaltene from crude oil represents it as a significant problem for the petroleum industry because of plugging up the well bore and reducing the efficiency of oil recovery [1- 3]. Therefore, the development of an effective method to control asphaltene flocculation is of a great economical importance to increase the overall efficiency of the oil recovery in field with asphaltene problem [3, 4]. Chemical inhibitors (dispersants), which are usually amphiphilic molecules, are often added to an oil well to prevent asphaltene deposition [2, 3, and 5]. The polar sites of asphaltenes interact with the polar inhibitor sites, while the nonpolar sites of inhibitors interact with the bulk oil phase [2, 4, and 6]. Thus, asphaltenes are stable in reservoir condition. However, during producing and refining crude oil, pressure drops, addition of diluents, crude oil chemical composition changes and oilfield operation conditions [7] may disrupt its stability. Therefore, asphaltene forms a solid and sticky phase which can be adsorbed or mechanically entrapped within the porous media of the reservoir [3, 7]. Numerous studies have been recently carried out on the application of solvents, dispersants and amphiphiles that decrease the asphaltene deposition. Amphiphiles are the surfactants with molecules consisting of two parts: a polar head and a nonpolar long-chain hydrocarbon tail, each part of which has an affinity for the different phases [8-11]. It has been reported that the activity of asphaltene flocculation inhibitor (AFI) is related to the maximum amount of inhibitors adsorbed on the asphaltene surface. They also showed that the larger AFI concentration at the asphaltene surface needed the larger volume of *n*-heptane to begin the flocculation of asphaltenes [9]. Chang and Fogler (1994) examined the effect of amphiphiles such as dodecyl benzene sulfonic acid (DBSA) and *p*-nonylphenol (NP) on asphaltene stabilization. They found that the polarity of the head and the length of the tail affected the effectiveness of the amphiphiles. It was also shown that DBSA was the most effective stabilizer for asphaltenes [10]. Some researchers investigated the DBSA as the asphaltene stabilizer and confirmed the observations of Chang and Fogler [6, 11, and 12]. They reported the effect of additives on the onset of asphaltene precipitation by the heat transfer technique. They used aromatics, heteroatomic compounds, hydrogen donor chemicals and surfactants as additives. Their findings showed that the addition of aromatic compounds delayed the onset of precipitation from highly asphaltic oils [10]. Phenanthrene addition (20 wt %) to bitumen delayed the onset of asphaltene, and appeared to be more effective than the additions of toluene, xylene or naphthalene. The effect of heteroatomic compounds and hydrogen donor chemicals (tetralin, decalin) was relatively small [13]. There has been some investigations on the dispersing of asphaltenes by various amphiphiles consisting of long alkyl chain benzenes, aliphatic alcohols, alkyl phenols and primary aliphatic amines. They also found that alkyl phenol with good peptizing properties prevented the asphaltene precipitation. Primary aliphatic amines are able to disperse asphaltenes, but long chain benzenes and aliphatic alcohols showed no asphaltene-dispersing ability. According to their study, the most obvious mechanism of the peptizing process was the interaction between the polar

functional groups on asphaltene surface and the polar head of amphiphiles to reduce the asphaltene polarity [14]. In addition, it was shown that nonylphenol (NP), DBSA and dodecyl resorcinol (DR) were better than resin to retard asphaltene precipitation, but toluene and deasphalted oil (DO) were not effective inhibitors [6]. Moreover, the inhibition of asphaltene precipitation by some compounds belonging to various chemical families including: non-ionic surfactants (ethoxylated alcohols and phenols), anionic surfactants (sulfonic and carboxylic acids), block copolymers (styrene/butadiene, oxyethylene /oxypropylene), block co-polymers with ionic groups (styrenesulfonic acid), other polymers including (hydroxyalkyl celluloses and siloxanes) and amines was tested. Among these compounds, nonionic surfactants such as ethoxylated alcohols and phenols showed the best performance. The results also revealed that effective inhibitors would need to display a significant interaction with both oil and asphaltenes [15]. Rocha et al. examined the inhibitory capacity of a number of new chemical additives on asphaltene precipitation. Their results showed that low molar mass ethoxylated nonylphenols, vegetable oils (coconut essential oil, sweet almond and sandalwood oil) and organic acids (linoleic, caprylic and palmytic acids) displayed the highest capacity to inhibit the asphaltene deposition. The remarkable solubilization effect displayed by DBSA, confirmed the importance of acid-based interactions in this process [16].

Increasing the alkyl tail length of amphiphiles can improve their dispersing potency. Likewise, increasing the polarity of amphiphiles' headgroup strengthens the attraction of amphiphiles to asphaltene through acid-based interaction and thus the ability of asphaltene dispersing is increased [17]. Laux et al. also confirmed the effect of the alkyl chain size on asphaltene precipitation. They attributed the good effect of 4-dodecyl resorcin, as a dispersing agent, to the higher dispersion and hydrogen bonding parts, and the influence of alkyl chain size [18]. It was shown that the dipole moment of resins had a strong effect on asphaltene precipitation [11]. The effectiveness of resin was defined in terms of the increase in the onset point of precipitation [12]. Smith et al. (2008) examined oil-specific asphaltene inhibitor chemistry of the two chemically distinct asphaltene inhibitors. Inhibitor A was polymer-based with protic polar heads and aliphatic tails and inhibitor B was a nonpolymeric amine with a polar head and an aliphatic tail. They found that protic inhibitor A would not react with acidic species in oil and therefore it was free to interact with asphaltene. They also identified some acidic and/or basic species that may be responsible for the observed difference in the inhibitor chemistry [2]. The adsorption of amphiphilic molecules is dependent not only on their functional groups, but also on the chemical structure (e.g., aromaticity and acidic groups) of the asphaltenes. Thus, any interaction between amphiphiles and functional groups plays an important role in asphaltene stability [18]. It was indicated that there were interactions between asphaltenes and naphthenic acids. They also suggested a relation between acid-based interactions and asphaltene type [19]. Although electric charge and potential may represent significant factors in the colloidal stability of crude oil and asphaltene dispersions, the nature (negative or positive), magnitude and the mechanism of formation of the electric charge on the surface of asphaltene particles is not understood yet [10,17]. Hernández-Trujillo analyzed the electrostatic, dispersion and repulsion contributions to the salvation energies as

a function of the alkyl chain length and the relationship with the electronic structure of the molecules [20]. The interaction energies are proportional to the amphiphiles' polarizability and dipole moment [9]. Their observations supported the hypothesis that the relative ability of a series of *p*-alkyl phenols to dissolve a given asphaltene in *n*-C7 is dominated by the amphiphile-solvent interaction. Accordingly, the high energy of asphaltene-dispersant interaction favors the efficiency of dispersant. It was recently shown that [20] petroleum asphaltenes are strong hydrogen-bond acceptors and weak hydrogen-bond donors. Actually, the conjugated structure that exists in asphaltenes may participate in the charge-transfer process corresponding to a partial removal of an electron from a bonding orbital [17]. Therefore, the acid-based interaction between asphaltenes and amphiphiles may result not only in the formation of hydrogen-bonding and charge-transfer interactions, but also in the irreversible electrophilic addition reaction. Charge-transfer mechanism yields saltlike compounds with asphaltene cation that are analogous to polyaromatic antracenes. Boukheissa et al. investigated the inhibition mechanism of the aggregation of petroleum asphaltenes using new ionic liquids (IL) (1-propyl boronic acid-3-alkylimidazolium bromides and 1-propenyl-3-alkylimidazolium bromides). The IL conjugated a good solubility in nonpolar environment with strong electron donor-acceptor properties. It was demonstrated that the presence of boronic acid moiety enhanced the interactions between asphaltene and ionic liquids. The length of the side alkyl chain of the ionic liquid was an important parameter as well. The minimum length of eight carbons was necessary to obtain sterical stabilization of IL-asphaltene complexes [3].

Although asphaltene precipitation has been under research during the last 30 years, the majority of the work in this field has dealt with closed systems (i.e. systems without flow) usually in the absence of a porous medium. Consequently, such results are not applicable to the production scale where flows as well as complex interactions between the fluid and the porous media are always present [7].

## **2. Research method**

### **2.1. Materials and Methods**

#### **2.1.1 Crude Oil**

In this study, the effects of addition of polyacrylamide with different concentrations on asphaltene deposition in a SiC pack column were investigated through 27 sets of experiments. The oil used in these experiments was provided from the Nowrouz oilfield located in South of Iran. Its physical properties are shown in Table 1. The oil flow rate, polymer concentration and electric charge of polymer (cationic, anionic and nonionic) were the main variables studied.

Table 1. Properties of the crude oil used in all experiments

Properties	Result	Test
Origin	Iran, Norouz field	-
Specific gravity @15.56 /15.56 °C	0.9323	ASTM D 4052
API	20.3	ASTM D 1298
Kinematic viscosity@ 20°C	381.7 mm <sup>2</sup> /Sec	ASTM D 445
Asphaltene content (w/w)	10.1%	IP 143
Nickel content (ppm)	29	UOP 800
Vanadium content (ppm)	115	UOP 800

The IP143 standard test was used to determine the asphaltene concentration.

### 2.1.2. Polymer Solutions

Polyacrylamide (provided by SNF Floerger) solutions in various concentrations (500, 2500 and 4000 ppm) were prepared by dissolving the required amount of polymer in distilled water. To remove all microgels, the polymer solutions were filtered at low injection rates through a 1.2 μm Whatman membrane filter using the vacuum suction. The properties and structure of polyacrylamides are shown in Table 2 and Figure1, respectively.

Table 2. Characteristics of polyacrylamide molecules

<i>Properties</i>	<i>Molecular weight</i>	<i>Trade name</i>	<i>Cationicity/ Anionicity in mole %</i>
<b>Anionic (APAM)</b>	10×10 <sup>6</sup>	AN 923	20%
<b>Neutral (PAM)</b>	10×10 <sup>6</sup>	FA 920	-
<b>Cationic (CPAM)</b>	10×10 <sup>6</sup>	FO 4650	55%

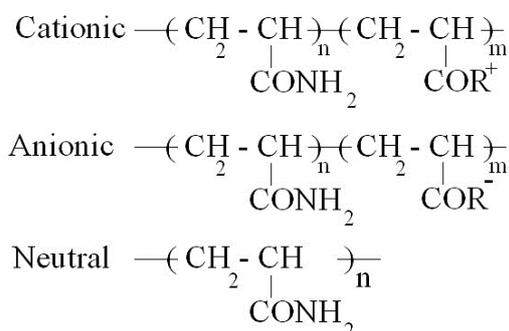


Figure 1. Molecular structure of the cationic, anionic, and nonionic polyacrylamides

### 2.1.3. Porous Media

SiC packs were made by dry packing SiC grains in a stainless steel core holder (2.25 cm in diameter and in length of 3 cm). The pore volume (PV) was about 8 cm<sup>3</sup>. For preparing the pack, a mixture of SiC grains with 40% of 707 μ

size, 30% of 45 $\mu$  size, and 30% of 15  $\mu$  size was used. After producing the adequate mixture, it was packed manually in the steel core.

#### 2.1.4. Coreflood Set-up and Procedure

A schematic diagram of the coreflood set up is shown in Figure 2. This set up enables experimentation in a single-phase flow through porous media over a range of pressure drops (0-90 psi). Pressure drop measurement was carried out by two pressure gauges with the accuracy of 0.05 bar. The main part of the facility is a core holder, which consists of a steel cylindrical body, that is fixed by two steel parts on both sides of core holder and sealed by two washers. In order to distribute the flow, a 1000 steel mesh was put in both sides of the core holder. A syringe pump was also used to inject oil and polyacrylamide solutions (0.01- 0.03 cc/min) into the sandpack. There was a pressure gauge at the end of the bed and a collector to store the output solution of the core.

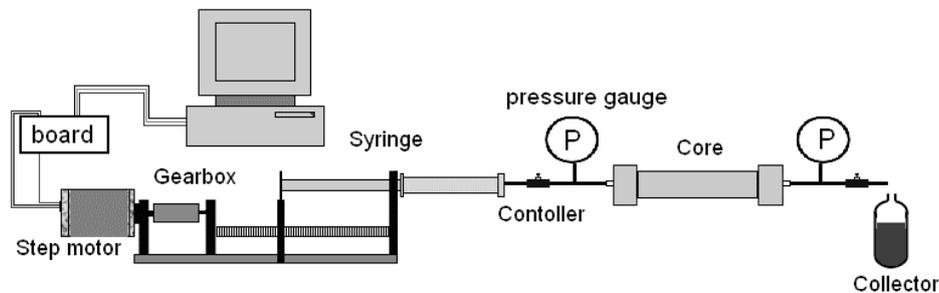


Figure 2. A Schematic set up including the synergic pump, core holder and output sample collector

The tests procedure consisted of the three following stages:

1. Crude oil injection with the flow rate of 0.02-0.2 cc/min,
2. Polymer injection with the flow rate of 0.02 cc/min,
3. Crude oil injection with the flow rate of 0.02-0.2 cc/min.

For the measurement of permeability and porosity, the pressure drops during the oil and polymer injections were continuously monitored.

### 3. Results and Discussion

#### 3.1. Anionic Polyacrylamide (APAM)

Figures 3-5 show the effects of APAM injection on the amount of asphaltene deposition in the porous media.

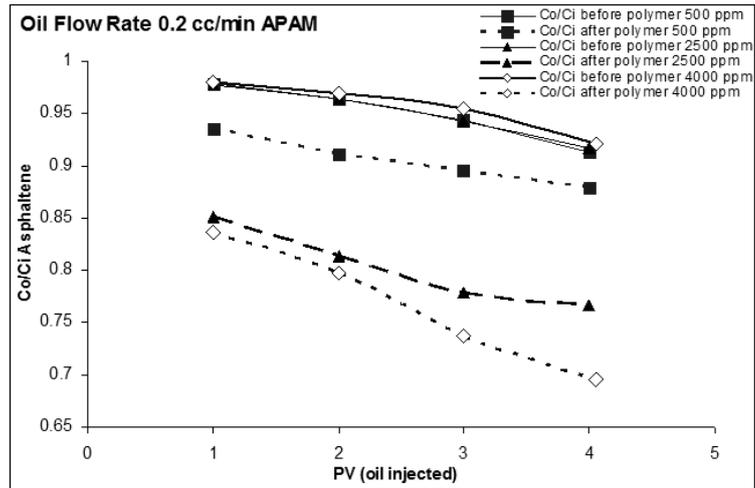


Figure 3.  $C_o/C_i$  of asphaltene vs. PV at the flow rate of 0.2 cc/min and the average permeability of 514 md

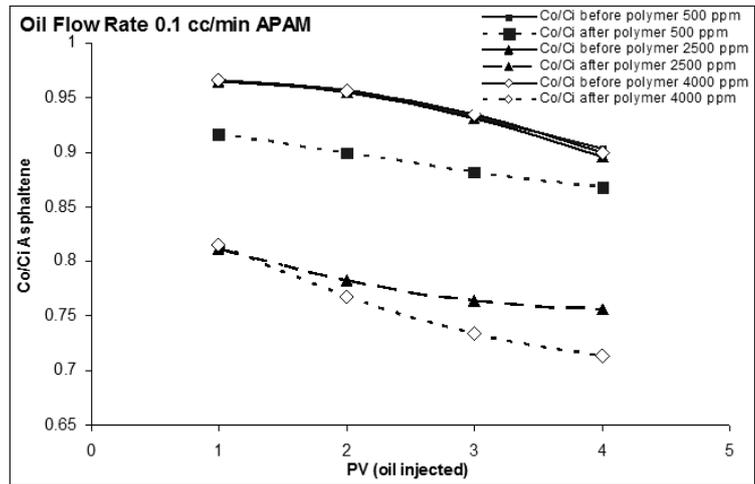


Figure 4.  $C_o/C_i$  of asphaltene vs. PV at the flow rate of 0.1 cc/min and the average permeability of 525 md

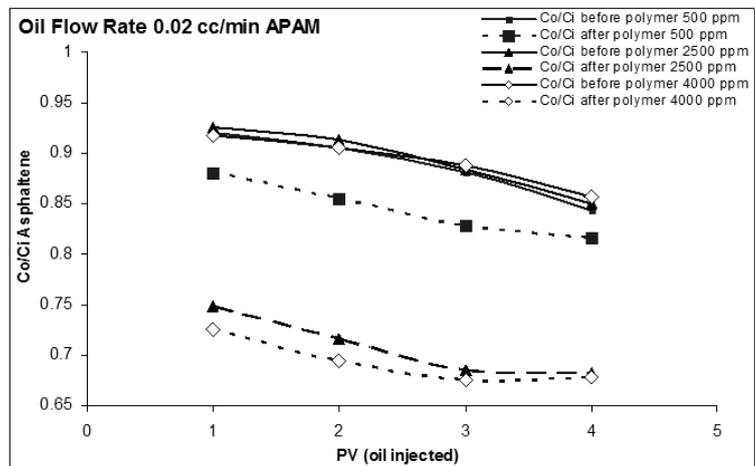


Figure 5.  $C_o/C_i$  of asphaltene vs. PV at the flow rate of 0.02 cc/min and the average permeability of 525 md

The trend of asphaltene output before polymer injection was almost similar. The slope of asphaltene concentration in the output, which indicates the amount of precipitated asphaltene in the packed bed, decreased steadily at first and then became intense. This shows that the precipitation mechanism before the polymer injection consisted of two stages: in the first stage, by entering oil into the sandpack, the asphaltene molecules were diffused into the pack from the bulk and then adsorbed onto the silica surface due to concentration gradient. As a result of low tendency of sandpack in the adsorption of asphaltene, linking of these molecules on SiC takes place through polar groups [9]. In the second stage, by injecting more and more of crude oil and increasing the asphaltene concentration of surface, the surface became more oilwet, due to changing of the wettability of surface caused by the asphaltene adsorption [21]. Therefore, the slope of the Figure increases after 3 and 4 PV. The difference of asphaltene deposits at various flow rates also shows the effect of oil flow rate on asphaltene precipitation in sandpacks. At higher injection rates, asphaltene precipitates faster, and by decreasing the flow rate, it drops. At lower injection rates, residence time of oil increases, so the asphaltene molecules have more time to settle on the surface. After polymer flooding, hydrophilic polymer adsorbed on the SiC grains and the amount of adsorbed polymer depend on the hydrophilic property of SiC. Anionic polymers are not suitable for the adsorption on silica, so APAM with the anionicity of 20% is used. Under natural conditions, polar resin molecules attach to asphaltene with their polar head and stabilize them [6]. When low concentrations of APAM are adsorbed on the surface, they do not have any significant effect on the stability, so the precipitation mechanism is similar to the pre-injection case. By increasing polymer concentration to 2500 ppm, the amount of output asphaltene in the primary PV noticeably decreased, indicating that APAM molecules can destabilize the equilibrium between the micelles and the bulk oil phase, leading to an increase in the concentration of asphaltene monomers in the bulk. Therefore, asphaltene adsorption on the surfaces increased. This causes an increase in charge density which in turn decreases the negative hydrophilic effect of the adsorbed polymers. At this concentration of anionic polymer, linking of one side of the polymeric chain to the surface causes the free sites of the adsorbed polymer [22] to be available near the surface, and absorb the asphaltene molecules existing in the bulk. At higher PV, a decrease in slope was observed, which was due to a reduction in the free sites of polymer for asphaltene absorption. Because of the opposite electric charge of both polymer and asphaltene, the chains of polymer have the tendency to entanglement (such as salts effects on polymer [23]). As a result, the less amount of asphaltene can be absorbed. This effect is more significant at higher flow rates.

At the polymer concentration of 4000 ppm, increasing the polarity can lead to a decrease in polymer adsorption [24]. At higher concentrations of polymer, entanglement will happen to the adsorbed polymers on the surface. Therefore, it causes a moderate decrease in their free chains. The mechanism of deposition can be divided into two steps. At first, the asphaltene molecules are adsorbed faster, (increased in slope), resulting in the decrease of free sites of polymer. Therefore, due to the polymer's polarity, the molecules of asphaltenes form a stable layer around the surface. As a result, asphaltenes diffuse from both the bulk and the stable layer into the pack. By increasing oil injection, concentration

near the surface grows and the direction of diffusion would be into the bulk, so the amount of asphaltene increases in the output. This effect is high at lower rates of oil, because of higher residence time. At higher concentrations (e.g. 2500 and 4000 ppm), more effect was observed in comparison with the 500 ppm, which can be related to the rise of charge density on the surface. It also causes the ion bridging adsorption in polyacrylamide, which has unfavorable effect on passing oil through the porous media. The asphaltene precipitation mechanism in high concentration of APAM is shown in Figure 6.

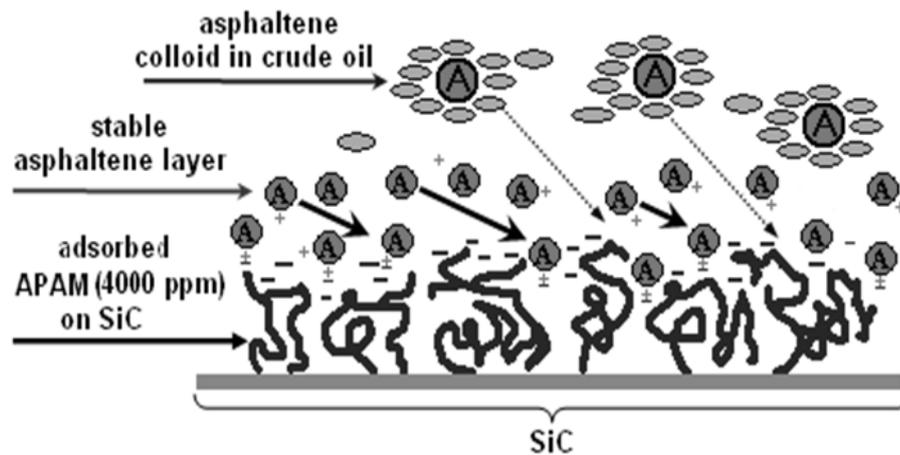


Figure 6. The mechanism of asphaltene precipitation in two steps: 1) Formation of a steady layer around the surface, 2) Diffusion from the formed stable concentration layer and bulk towards the surface

### 3.2. Neutral polyacrylamide (PAM)

To study the effect of charge density of the adsorbed polymer on surface on the asphaltene precipitation formation into the pack, a polyacrylamide without charged side chains was used.

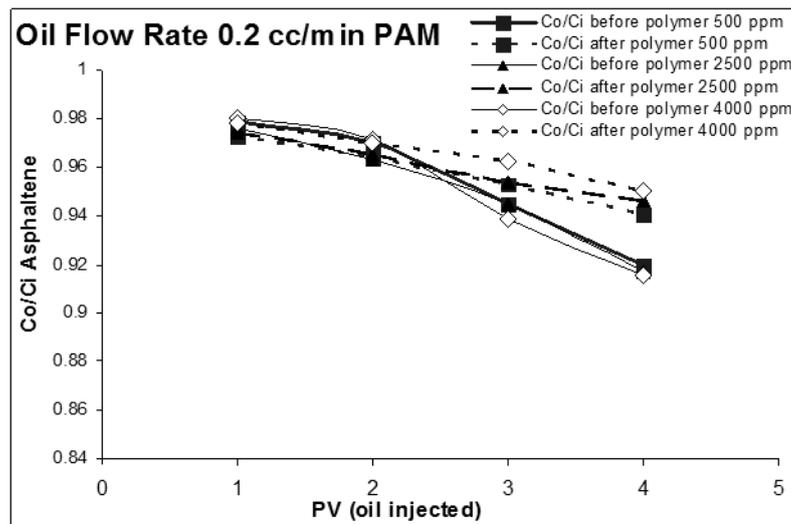


Figure 7.  $C_o/C_i$  of asphaltene vs. PV at the flow rate of 0.2 cc/min and the average permeability of 512 md

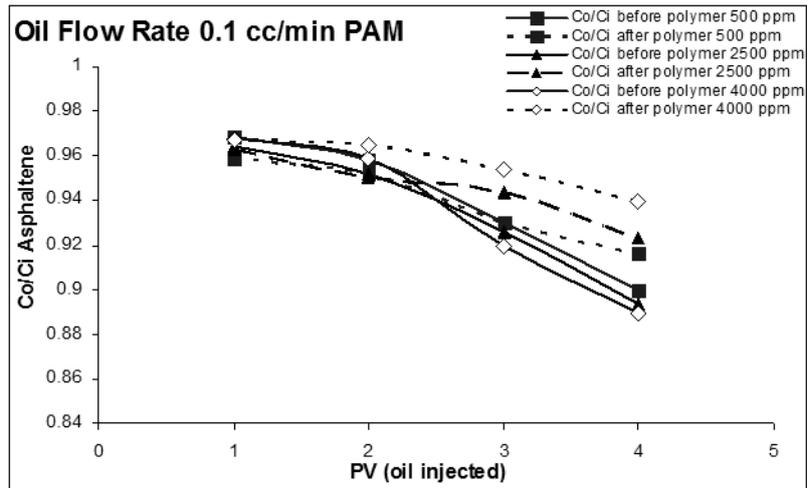


Figure 8.  $C_o/C_i$  of asphaltene vs. PV at the flow rate of 0.1 cc/min and the average permeability of 517 md

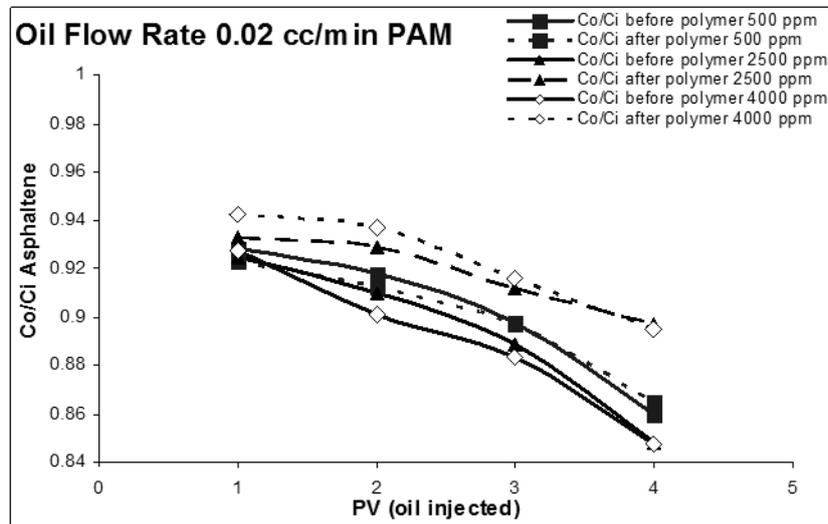


Figure 9.  $C_o/C_i$  of asphaltene vs. PV at the flow rate of 0.02 cc/min and the average permeability of 532 md

The effects of various flow rates of PAM on asphaltene deposition in the concentration of 500 ppm are shown in Figures 7-9. In the beginning, due to changing wettability of the surface, lower amounts of asphaltene are absorbed on the pack, but after initiation of the precipitation, the tendency of the asphaltene molecules for precipitation increases, which can be clearly observed in variety of slopes. At low rates (0.02 cc/min), this effect is stronger. The slope drops rapidly with an increase in oil injection. The ability of SiC grains in altering the wettability of surface rises at higher polymer concentrations. The adsorbed molecules also produce spherical entanglement near the surface by dispersing their tails. This steric hindrance decreases the possibility of asphaltene precipitation, so as the injection continues, the slope is enhanced by increasing the relative asphaltene adsorption. Because of the nonionic property of the polymer, it has neither the ability of sorption through the substitution functional groups nor adsorption or repulsion through electrostatic interaction. It seems that the difference in

wettability of sandpack may be the main reason for this behavior of the polymer. At first, a low amount of asphaltene was observed in the output (at lower flow rates), which indicated the dominant effect of these polymers on decreasing the asphaltene adsorption. The decrease in slope shows the positive effect of PAM on the precipitation of asphaltene. It is expected that the low flow rate of 0.02 cc/min is more effective, but a comparison between the diagrams does not confirm this, which can be related to the required time for asphaltene molecules to diffuse through the outer layers and adsorption on the pack. Regarding the trapped asphaltene molecules in the pore throat, at higher rates they join the bulk because of flow pressure. Therefore, the amount of asphaltene increases in the output, as shown in Figures 7 and 8.

In a constant flow rate, the amount of output asphaltene rises by increasing the polymer concentration, i.e. lower precipitation in the bed. By injecting PAM, the output of the asphaltene decreases at first. Then, it is similar to the case in which no polymer injection is done into the core. However, there is a reduction in the slopes in comparison with pre-injection case, which indicates the positive effect of this polymer on the deposition of asphaltene. The diffusion and adsorption mechanisms of nonionic polyacrylamide at different concentrations are shown in Figure 10.

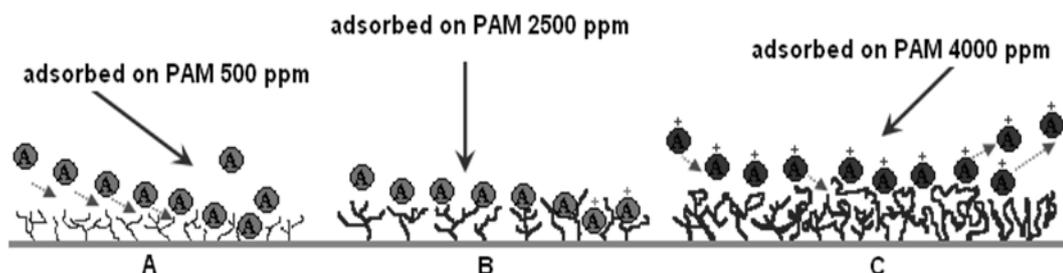


Figure 10. The mechanism of asphaltene precipitation on silica sandpack covered by nonionic polyacrylamide (PAM), A) Variation in wettability property decreases the precipitation, B) Increasing the wettability variation of sandpack and then reduction of precipitation and C) The spherical entanglement of asphaltene molecules with the free sites of PAM as a multiple agent for preventing the asphaltene precipitation

### 3.3. Cationic polyacrylamide (CPAM)

The cationic polyacrylamide with the cationicity of 55% was used to study the effect of polymer charge density on the asphaltene precipitation in porous media. The use of high charge density of this polymer is for no surface prohibition in the adsorption of the CPAM.

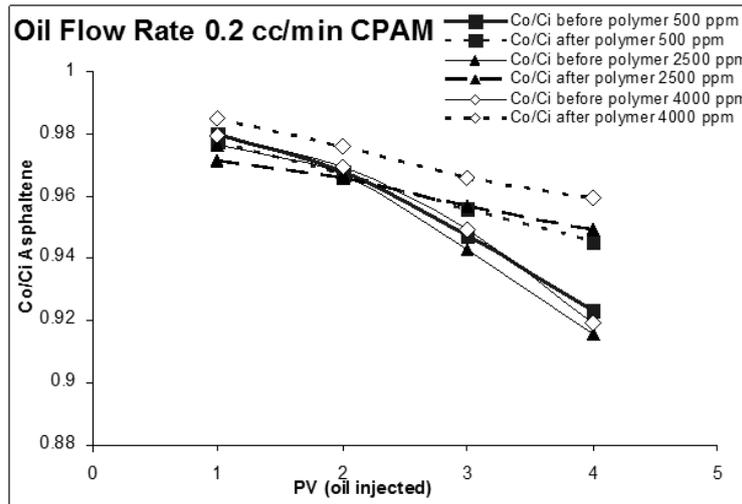


Figure 11.  $C_o/C_i$  of asphaltene vs. PV at the flow rate of 0.2 cc/min and the average permeability of 510 md

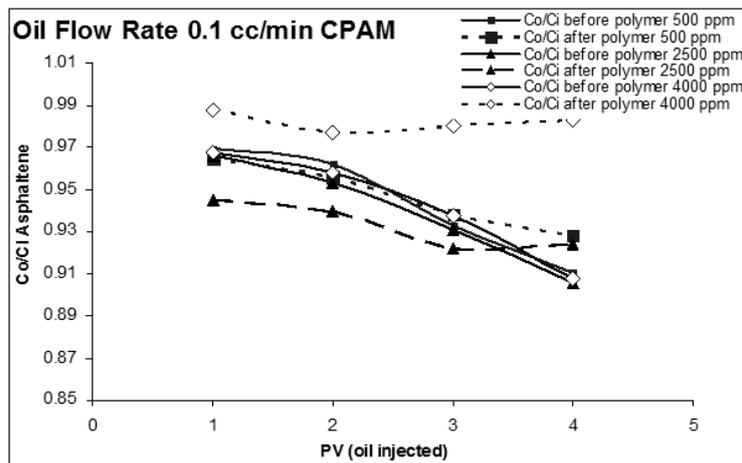


Figure 12.  $C_o/C_i$  of asphaltene vs. PV at the flow rate of 0.1 cc/min and the average permeability of 494 md

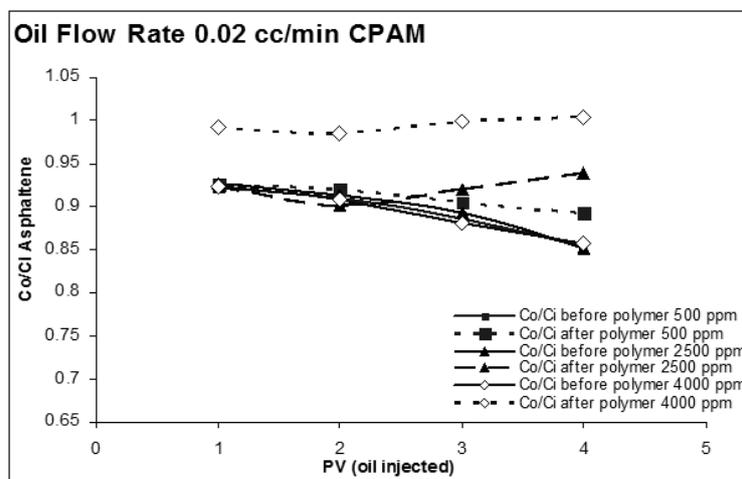


Figure 13.  $C_o/C_i$  of asphaltene vs. PV at the flow rate of 0.02 cc/min and the average permeability of 514 md

According to Figures 11 to 13, at 500 ppm concentration of cationic polymer, there is an unexpected reduction in the output precipitation. The asphaltene precipitation in sandpack can be caused by its tendency for sedimentation on the surface and also on the already adsorbed asphaltene molecules. The high cationicity shows a competition between the adsorbed CPAM and the asphaltenes on the surface, where CPAM overcomes the asphaltene while in anionic polymers, although there is a similar competition between adsorbed APAM and resins, because of low anionicity at 500 ppm, APAM does not dominate over the resins. At 500 ppm concentration, the slope of diagrams is similar to PAM injection. Whereas in cationic polymer, similar slopes at different flow rates show that the residence time can be considered as an effective parameter in precipitation at various flow rates. At 2500 ppm, reduction of slope after polymer injection can be related to the electrostatic repulsion between either the adsorbed polymers or the hydrophilic property of the surface. Both of these have the same effect in preventing asphaltene deposition. In Figures 12 and 13, the change in the direction of curves may be due to an interaction between the asphaltene and the polymer molecules [10]. As a result, it can be stated that repulsion and acid-based reaction are the dominant mechanisms. At low flow rates, the output ratio more than one is probably because of the returning of asphaltene molecules suspended around the pack or separated asphaltenes from the pack that move into the bulk.

#### 4. Conclusion

The primary aim of this study was to investigate the effect of polar polyacrylamide on asphaltene precipitation in porous media. Based on the experiments conducted and the results obtained for SNF polyacrylamide, the following conclusions are made:

1. Increasing the resident time of the oil in porous media at lower flow rates (e.g. 0.02 cc/min) causes an increase in asphaltene precipitation.
2. Asphaltene precipitation increases in the core by increasing APAM concentration with the 20% anionicity. At 2500 ppm concentration, positively charged asphaltene molecules are adsorbed on the free sites of polymer near the surface. At higher concentrations (4000 ppm), in higher PV, deposition is because of the steady layer forming of asphaltene around the surface and diffusion from the bulk. Thereafter, concentration gradient reverses some of the precipitation moves toward the bulk. However, the effect of the returning asphaltenes in comparison with the precipitated asphaltenes is negligible.
3. Use of nonionic polyacrylamide causes a precipitation, because of the only mechanism available in the porous media that could be the wettability changing of the surface after polymer adsorption from waterwet to oilwet. Increasing the polymer concentration leads to a decrease in the deposition which may happen in the growing of coated polymers.
4. At the low concentration of CPAM (500 ppm), the asphaltene precipitation decreases, but the electrostatic repulsion mechanism is not dominant. At 2500 ppm polymer concentration, the amount of deposition increases unexpectedly, which may be related to the suggested interaction mechanism between the polymer and asphaltene. After some PV, the

interaction product departs from the surface and enters into the bulk. At 4000 ppm, the interaction mechanism dominates the repulsion mechanism since this increased concentration causes the entanglement of polymers which leads to a decrease in free sites; consequently, the tendency of asphaltene for adsorption decreases.

5. Since APAM increases the asphaltene precipitation in the porous media, their EOR (Oil Enhanced Recovery) is not recommended. At low rates, CPAM with the concentration of 2500 ppm and at very low rates, CPAM with 4000 ppm concentration have behaved better. It is worth mentioning that increasing polymer concentration causes problems in oil flow.
6. Asphaltenes are charged molecules that act as a positive aromatic aggregate. However, in the presence of cationic polymers, they behave as polyaromatic aggregation with the source of electrons.

## 5. Acknowledgements

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## References

- [1] J. G. Speight, *The chemistry and technology of petroleum*: CRC press, 1999.
- [2] S. Turgman-Cohen, D. A. Fischer, P. K. Kilpatrick, and J. Genzer, "Asphaltene Adsorption onto Self-Assembled Monolayers of Alkyltrichlorosilanes of Varying Chain Length," *ACS Applied Materials & Interfaces*, vol. 1, pp. 1347-1357, 2009.
- [3] M. Boukherissa, F. Mutelet, A. Modarressi, A. Dicko, D. Dafri, and M. Rogalski, "Ionic Liquids as Dispersants of Petroleum Asphaltenes," *Energy & Fuels*, vol. 23, pp. 2557-2564, 2009.
- [4] M. Barcenas, P. Orea, E. Buenrostro-González, L. S. Zamudio-Rivera, and Y. Duda, "Study of Medium Effect on Asphaltene Agglomeration Inhibitor Efficiency," *Energy & Fuels*, vol. 22, pp. 1917-1922, 2008.
- [5] J. C. Pereira, I. López, R. Salas, F. Silva, C. Fernández, C. Urbina, et al., "Resins: The Molecules Responsible for the Stability/Instability Phenomena of Asphaltenes†," *Energy & Fuels*, vol. 21, pp. 1317-1321, 2007.
- [6] T. A. Al-Sahhaf, M. A. Fahim, and A. S. Elkilani, "Retardation of asphaltene precipitation by addition of toluene, resins, deasphalted oil and surfactants," *Fluid Phase Equilibria*, vol. 194–197, pp. 1045-1057, 2002.
- [7] N. I. Papadimitriou, G. E. Romanos, G. C. Charalambopoulou, M. E. Kainourgiakis, F. K. Katsaros, and A. K. Stubos, "Experimental investigation of asphaltene deposition mechanism during oil flow in core samples," *Journal of Petroleum Science and Engineering*, vol. 57, pp. 281-293, 2007.
- [8] O. León, E. Contreras, E. Rogel, G. Dambakli, J. Espidel, and S. Acevedo, "The Influence of the Adsorption of Amphiphiles and Resins in Controlling Asphaltene Flocculation," *Energy & Fuels*, vol. 15, pp. 1028-1032, 2001.
- [9] O. León, E. Contreras, and E. Rogel, "Amphiphile adsorption on asphaltene particles: adsorption isotherms and asphaltene stabilization," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 189, pp. 123-130, 2001.
- [10] C.-L. Chang and H. S. Fogler, "Stabilization of Asphaltenes in Aliphatic Solvents Using Alkylbenzene-Derived Amphiphiles. 2. Study of the Asphaltene-Amphiphile

- Interactions and Structures Using Fourier Transform Infrared Spectroscopy and Small-Angle X-ray Scattering Techniques," *Langmuir*, vol. 10, pp. 1758-1766, 1994.
- [11] L. Goual and A. Firoozabadi, "Effect of resins and DBSA on asphaltene precipitation from petroleum fluids," *AIChE Journal*, vol. 50, pp. 470-479, 2004.
- [12] S. Peramanu, P. F. Clarke, and B. B. Pruden, "Flow loop apparatus to study the effect of solvent, temperature and additives on asphaltene precipitation," *Journal of Petroleum Science and Engineering*, vol. 23, pp. 133-143, 1999.
- [13] P. F. Clarke and B. B. Pruden, "Asphaltene precipitation: detection using heat transfer analysis, and inhibition using chemical additives," *Fuel*, vol. 76, pp. 607-614, 1997.
- [14] G. González and A. Middea, "Peptization of asphaltene by various oil soluble amphiphiles," *Colloids and Surfaces*, vol. 52, pp. 207-217, 1991.
- [15] A. Carlos da Silva Ramos, L. Haraguchi, F. R. Notrispe, W. Loh, and R. S. Mohamed, "Interfacial and colloidal behavior of asphaltenes obtained from Brazilian crude oils," *Journal of Petroleum Science and Engineering*, vol. 32, pp. 201-216, 2001.
- [16] L. C. Rocha Junior, M. S. Ferreira, and A. C. da Silva Ramos, "Inhibition of asphaltene precipitation in Brazilian crude oils using new oil soluble amphiphiles," *Journal of Petroleum Science and Engineering*, vol. 51, pp. 26-36, 2006.
- [17] J. Wang, C. Li, L. Zhang, G. Que, and Z. Li, "The Properties of Asphaltenes and Their Interaction with Amphiphiles," *Energy & Fuels*, vol. 23, pp. 3625-3631, 2009.
- [18] H. Laux, I. Rahimian, and T. Butz, "Theoretical and practical approach to the selection of asphaltene dispersing agents," *Fuel Processing Technology*, vol. 67, pp. 79-89, 2000.
- [19] O. León, E. Contreras, E. Rogel, G. Dambakli, S. Acevedo, L. Carbognani, et al., "Adsorption of Native Resins on Asphaltene Particles: A Correlation between Adsorption and Activity," *Langmuir*, vol. 18, pp. 5106-5112, 2002.
- [20] J. Hernández-Trujillo, J. M. Martínez-Magadán, and I. García-Cruz, "Molecular Characterization of p-Alkyl Phenol-n-Heptane Interactions and Their Implication as Asphaltene Dispersants," *Energy & Fuels*, vol. 21, pp. 1127-1132, 2007.
- [21] T. Pernyeszi, Á. Patzkó, O. Berkesi, and I. Dékány, "Asphaltene adsorption on clays and crude oil reservoir rocks," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 137, pp. 373-384, 1998.
- [22] B. Brotherson and Y. Deng, "Site blocking effect on the conformation of adsorbed cationic polyacrylamide on a solid surface," *Journal of Colloid and Interface Science*, vol. 326, pp. 324-328, 2008.
- [23] N. Mungan, F. W. Smith, J. L. Thompson, O. Sinclair, and C. Gas, "Some aspects of polymer floods," *Journal of Petroleum Technology*, vol. 18, pp. 1143-1150, 1966.
- [24] A. Zaitoun and N. Kohler, "The Role of Adsorption in Polymer Propagation Through Reservoir Rocks," presented at the SPE International Symposium on Oilfield Chemistry, San Antonio, Texas, 1987.

## بررسی اثر تزریق پلی اکریل آمید همراه با بار الکتریکی بر رسوب آسفالتن در محیط متخلخل

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### چکیده

در این مطالعه اثر سه پلی اکریل آمید قطبی مختلف (دارای آنیون فعال، دارای کاتیون فعال و غیر یونی) بر رسوب آسفالتین در محیط متخلخل بررسی شده است. تمام آزمایش‌ها در دبی‌های مختلف جریان نفت مرده (۰/۲ cc/min، ۰/۱ و ۰/۰۲) و همچنین غلظت‌های متفاوت پلیمر (۵۰۰ ppm، ۲۵۰۰ و ۴۰۰۰) انجام گرفت. نتایج نشان دادند که رسوب آسفالتین به شدت متاثر از حضور افزودنی‌های قطبی نظیر پلی اکریل آمید بار دار شده می‌باشد. به طور کلی، پلی اکریل آمید آنیونی رسوب آسفالتین را زیاد کرد و مقدار آن نسبت مستقیمی با غلظت پلی اکریل آمید آنیونی دارد. پلی اکریل آمید آنیونی با غلظت‌های ۲۵۰۰ و ۴۰۰۰ ppm نقش تشدید کننده را داشت، در حالی که خاصیت آبدوستی پلی اکریل آمید آنیونی نقش ممانعت کننده در ته نشینی آسفالتین را بازی کرد. پایداری رسوب آسفالتین در حضور پلی اکریل آمید کاتیونی تخریب شد. به علاوه، مکانیسم‌های الکترواستاتیکی و اسید - بازی اثر بازگشتی بر رسوب آسفالتین داشتند. پارامتر اثرگذار دیگر دبی جریان بود که در کنار سایر پارامترها در این پژوهش در نظر گرفته شد.