

# Effect of capillary number on the residual oil saturation during chemical flooding

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**Abstract.** The paper presents experimental results of studying capillary displacement curves in chemical methods of enhancing oil recovery. The analysis of the theory of capillary number and changes in this parameter in chemical methods of enhancing oil recovery is carried out. The results of studies of capillary displacement curves are analyzed, and general patterns and features of the behavior of these curves in various experimental conditions are revealed. The analysis showed that with a change in formation wettability, porosity, permeability, and pore structure, the capillary displacement curves change. Under changing formation conditions, classical capillary displacement curves previously obtained in the course of basic experiments do not allow predicting residual oil saturation, and in addition, the maximum oil recovery does not correspond to the maximum values of capillary numbers. In the practice of oil field development, there is no need to use high concentrations of surfactants to reduce the surface tension to an ultra-low level. Addition of polymer, and alkali (in appropriate concentration) provides high oil recovery due to interaction of surfactants, polymer and alkali. Currently, in China, ASP flooding technology (alkaline-surfactant-polymer flooding – alkaline flooding and combined use of alkali, surfactant, and polymer) is the most effective method of enhancing oil recovery in flooded oil fields and gives good results. Therefore, it is necessary to study the micromechanisms of residual oil mobility and filtration. Studies of the capillary displacement curve, considering the structure of the reservoir and its basic filtration characteristics, are of decisive importance in the development of oil fields in China, and these curves can also be used in world practice as a basis for enhancing oil recovery.

**Keywords:** the curves of capillary displacement, EOR, capillary number, ultra-low interfacial tension types

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## Introduction

The large-scale use of oil resources has led to an increase in the shortage of recoverable reserves, and increasing oil recovery is becoming a priority area of oilfield research.

Most oil fields in China are at the stage of chemical flooding. The addition of chemical reagents significantly increases the oil recovery factor, especially when using polymers, surfactants, and alkalis. Chemical flooding substantially enhances oil recovery compared

to conventional flooding and can serve as an effective method for extracting residual oil.

Since the introduction of the capillary number concept, numerous studies have been conducted to investigate the mechanisms of residual oil formation and its filtration at different capillary numbers (Mikhailov, 1992). Based on the capillary number concept and using capillary displacement curves (the dependence of residual oil saturation on the capillary number), various correlations between these parameters have been established, which can serve as a basis for digital modeling of chemical flooding. Based on the capillary number concept and using capillary displacement curves (the dependence of residual oil saturation on the capillary number), various correlations between these parameters have been established, which can serve as a basis for

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digital modeling of chemical flooding (Guo et al., 2022).

According to the fundamental theory of capillary numbers, the primary cause of residual oil retention in pores is capillary forces. The well-known mechanism of oil displacement indicates that for the porous system, the effectiveness of oil displacement is determined by the ratio of driving pressure gradient to capillary retaining force. The driving pressure gradient is proportional to the viscosity of the displacing fluid and its flow rate. The retaining force of residual oil is mainly proportional to the interfacial tension between the fluids.

Based on the above, a dimensionless capillary number has been proposed and applied by various researchers (Chatzis, Kuntamukkula, 1988; Mikhailov, 2011).

$$N_c = \frac{\mu v}{\sigma}, \quad (1)$$

where  $N_c$  is the capillary number,  $\mu$  is the viscosity of the displacing fluid [mPa·s],  $v$  is the flow rate of the displacing fluid [m/s],  $\sigma$  is the interfacial tension between fluids [mN/m].

Let us consider the patterns of oil displacement with varying capillary number.

### Oil Displacement by Water

The oil displacement coefficient by water under laboratory conditions is determined by the following equation:

$$K = 1 - \frac{S_{or}}{S_{oi}}. \quad (2)$$

The displacement coefficient value  $K$  is determined based on initial oil saturation  $S_{oi}$  and residual oil saturation  $S_{or}$ , which are traditionally considered petrophysical characteristics of the reservoir. This approach is commonly used in the design and analysis of oil field development (Mikhailov, 1983).

Professor Mikhailov N.N. proposed a different concept: residual oil saturation is not a petrophysical characteristic of the reservoir, and the oil displacement coefficient by water is not controlled solely by the reservoir's filtration-capacitive properties (Mikhailov, 1983, 1982). Mikhailov's publications note that the displacement coefficient depends not only on reservoir properties but also on oil displacement conditions: displacement rate, oil-to-water viscosity ratio, interfacial tension at the phase boundary, etc. (Mikhailov, 2011, 2021, 1992; Melekhin, 2015) (Fig. 1).

Core samples from complex carbonate reservoirs of the Timan-Pechora oil and gas province were investigated. All selected cores exhibited hydrophobic properties, with experiments conducted under reservoir thermobaric conditions. The experimental results revealed relationships between the displacement coefficient and capillary number in double logarithmic coordinates. These dependencies differ from classical

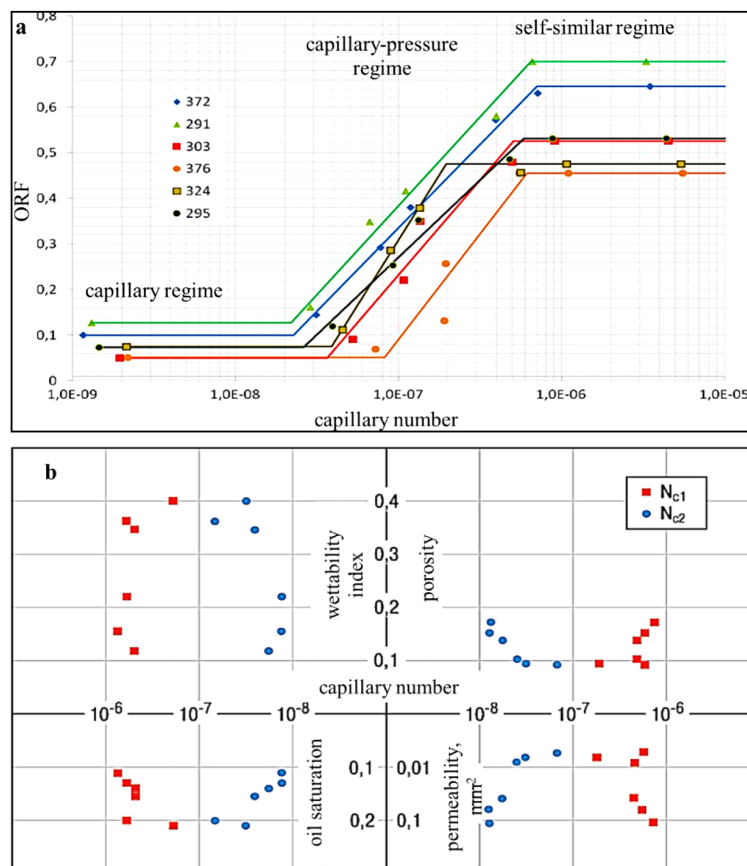


Fig. 1. a – Oil recovery factor (ORF) versus capillary number; b – Critical capillary number values versus core parameters

capillary curves by differentiation according to residual oil saturation formation regimes. As shown in Figure 1, three distinct displacement coefficient formation regimes are identified: capillary, capillary-pressure, and self-similar regimes, separated by critical capillary number thresholds (residual oil mobilization threshold  $N_{c1}$  and residual oil displacement threshold  $N_{c2}$ ). In the capillary regime (low displacement rates approaching capillary imbibition rates), hydrodynamic pressure gradients can be neglected. This regime produces low displacement coefficient values. As displacement rates increase up to the first critical threshold, displacement coefficients remain virtually unchanged. This critical capillary number value ( $N_{c1}$ ) has been designated by the author as the residual oil mobilization threshold. The capillary-pressure regime demonstrates displacement coefficient growth with increasing displacement rates from the first to second critical thresholds, driven by the involvement of conditionally mobile residual oil fractions. This regime maintains capillary-pressure equilibrium. The second critical capillary number ( $N_{c2}$ ) represents the threshold for displacing capillary-trapped oil. Further increases in displacement rates lead to a transition to the self-similar regime, achieving maximum displacement coefficient values, while the remaining oil becomes firmly bound (Mikhailov, 1992).

Experimental results of residual oil mobilization during waterflooding indicate that the mobilization threshold varies with changes in reservoir filtration-capacity and surface properties, along with altered sensitivity of residual oil saturation to displacement conditions.

Formula (1) and (2) provide quantitative measures of technological efficiency for waterflooding oil displacement, rather than ASP flooding or other chemical reagent injection modifications. For these purposes, universal formulas have been developed to evaluate displacement coefficient changes and their increments,

as presented in the referenced studies (Shakhverdiev, Mandrik, 2007; Shakhverdiev, 2014).

### Chemical Flooding

Chemical enhanced oil recovery (EOR) methods represent critical components of comprehensive EOR systems and are widely employed in oil fields globally. These methods play a pivotal role in recovering residual oil after waterflooding, serving as tertiary recovery techniques. Consequently, analyzing the dependence of residual oil saturation on capillary number (displacement curve) during chemical flooding is of particular importance (Mo Jiali et al., 2024).

According to the widely accepted capillary number formula (1), in chemical flooding, an increase in  $N_c$  is achieved by reducing interfacial tension or enhancing the viscosity of the displacing fluid. Due to variations in reservoir conditions (properties of oil, water, and rock), the efficiency of applied EOR methods varies significantly. Chemical flooding encompasses the following technologies: polymer flooding, surfactant flooding, alkaline flooding, binary compound flooding (alkali/polymer, polymer/surfactant, alkali/surfactant), and ASP flooding (alkali/surfactant/polymer), among others.

Among these EOR methods, polymer flooding stands out as an effective approach for enhancing oil recovery. Furthermore, polymer flooding is well-suited to the geological and operational conditions of most oil fields. Owing to its simplicity and cost-effectiveness, this technology has been widely implemented in China. Although many reservoir blocks in Chinese fields are at a high water-cut stage, residual oil saturation remains approximately 65% (Mikhailov, 1982). To recover this residual oil, it is essential to justify tertiary EOR technologies tailored to the structure of the remaining oil. Polymer flooding enables the extraction of residual oil and increases the post-waterflooding recovery factor by more than 10% (Fig. 2).

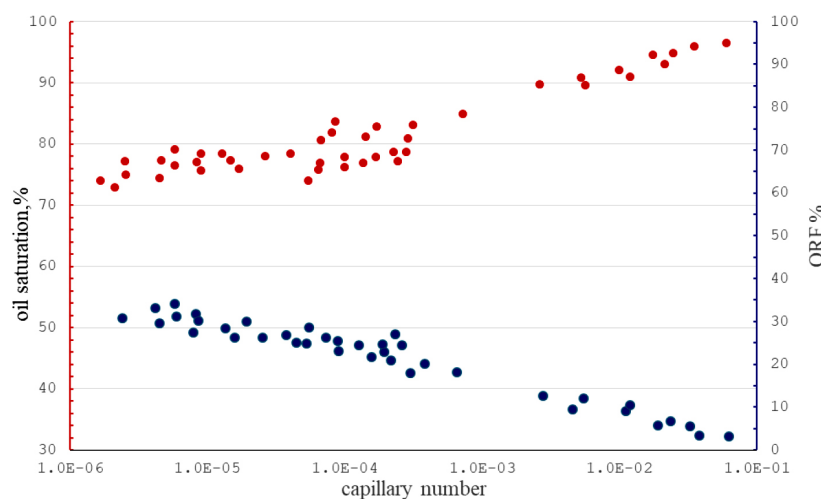


Fig. 2. Capillary number, oil saturation, and ORF versus core (Daqing oil field core, China)

## Surfactant Flooding

Surfactants are generally acknowledged to perform two primary functions: reducing oil-water interfacial tension to ultra-low levels ( $\leq 10^{-3}$  mN/m) (Liu et al., 2017) and altering reservoir wettability through adsorption at oil-water-rock interfaces. These effects increase capillary numbers and enhance oil recovery. It is established that during conventional waterflooding, the capillary number is approximately  $10^{-7}$  (Mikhailov, 1985). To reduce residual oil saturation from 65% to 30% (or lower), a 3–4 order-of-magnitude increase in capillary number is required (Chatzis, Morrow, 1984; Foster, 1973). Under actual field conditions, achieving significant increases in displacing fluid viscosity or flow rate is highly challenging; thus, interfacial tension reduction by 3–4 orders of magnitude is typically prioritized.

Field experience in EOR practices in China has demonstrated that surfactant flooding can significantly improve oil recovery even without attaining ultra-low interfacial tension. For example, a combination of 0.4% petroleum sulfonate solution and polymer solution was employed at the Shengli Oilfield in China. While interfacial tension did not reach ultra-low levels, the

recovery factor nevertheless increased by approximately 18%. Laboratory experiments have yielded analogous results.

Laboratory core flooding experiments were conducted using naphthylaryl sulfate (NAS) and salt-tolerant polyacrylamide (KYPAM) to formulate a polymer-surfactant composite flooding system (Gong et al., 2020; Zhan et al., 2021). In Figure 3(a), the intersection point derived by extrapolating lines at low and high paraffinic oil concentrations represents the maximum capacity of solubilization. Even without reaching maximum solubilization, NAS micelles can further solubilize a portion of paraffinic oil, with such micelles termed “swollen micelles” (Tehrani-Bagha et al., 2012). The swelling capacity of micelles must be accounted for in chemical flooding, particularly in experiments with sufficiently low surfactant concentrations. As depicted in Figure 3(c), interfacial tension at optimal surfactant concentrations does not reach ultra-low values. However, Figures 3(d) and 3(e) indicate that all recovery factors surpass 24%. Notably, increasing surfactant concentration from 0.1% to 1.0% results in an initial reduction followed by an increase in interfacial tension (Figure 3(f)), while the displacement coefficient

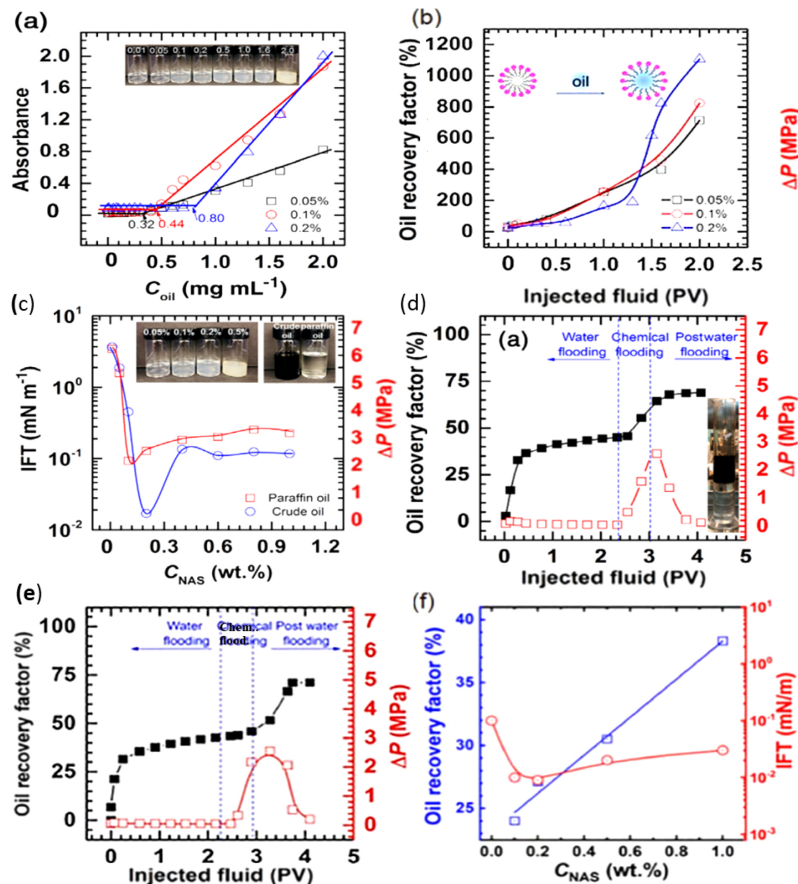


Fig. 3. a – Change in absorption and b – NAS size in 0.05%, 0.1%, and 0.2% NAS solutions versus paraffin content in model paraffin (white) oil; c – dynamic interfacial tension of NAS/white oil and NAS/natural (crude) oil solutions at different NAS concentrations; recovery efficiency and displacement pressure, respectively, for 0.1% (d) and 1.0% (e), NAS solution in 0.24% polymer solution; f – relationship between recovery factor and interfacial tension as a function of NAS concentration. The water model is a 14,000 mg/L NaCl solution; the temperature for all experiments is 40°.

exhibits a linear rise with surfactant concentration. These experimental findings confirm that ultra-low interfacial tension is not a mandatory condition for enhanced oil recovery. Thus, practical field applications can achieve incremental oil production even without attaining ultra-low interfacial tension. To optimize recovery, solubilization efficiency may be improved by adjusting surfactant concentration within a specified operational range.

Chemical flooding also enables modification of reservoir wettability through surfactant incorporation.

Among reservoirs with diverse wettability characteristics, weakly hydrophilic formations demonstrate the highest oil recovery factors (ORF).

In laboratory core displacement tests employing a 0.06% DTAB (dodecyltrimethylammonium bromide) system, the initial hydrophilic wettability of core surfaces transitioned to neutral. This shift expanded the two-phase zone on relative permeability curves and enhanced oil mobility at constant water saturation. Increased hydrophilicity reduces adhesive forces between oil droplets and rock surfaces, facilitating oil displacement. In hydrophilic cores, capillary forces further promote oil mobilization (Fig. 4) (Deng et al., 2022).

Conversely, progressive enhancement of hydrophobicity in the pore surfaces of core samples results in stronger oil adsorption on internal pore walls, accompanied by a continuous decline in the relative permeability of the oil phase. In hydrophobic rock formations, water is distributed as discrete droplets within pore centers. The intricate pore structure adversely affects residual oil displacement, as the diameter of residual oil droplets exceeds the pore throat dimensions (Rücker et al., 2020).

### Polymer Flooding

In most oil fields, achieving substantial pressure gradient enhancement in the interwell region is impractical, leading to the widely accepted assumption that the interwell pressure gradient remains effectively constant. Pressure gradient increases are feasible only within limited near-wellbore zones, which improves localized oil displacement efficiency in these areas but exerts negligible influence on reservoir-scale displacement performance. Consequently, pressure gradient elevation cannot be utilized as a viable mechanism for enhancing overall reservoir oil recovery (Mikhailov, 1985).

The improvement in oil displacement efficiency during polymer flooding arises exclusively from microscopic forces. While multiple microscopic forces act within the reservoir, only those that do not amplify macro-pressure gradients can account for the mechanism by which viscoelastic fluids enhance oil recovery.

Streamline patterns and microscopic forces generated

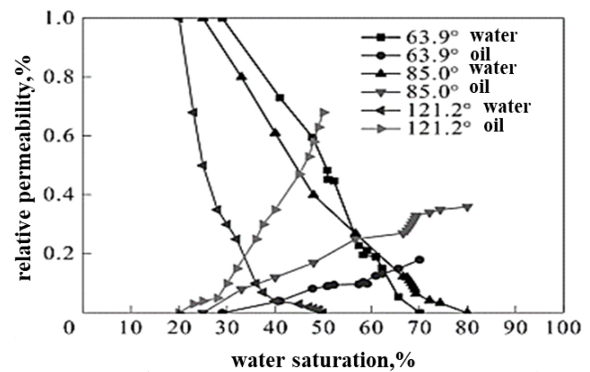


Fig. 4. Relative permeability curves for surfactant flooding for different contact angles

by different fluids can undergo modification solely under conditions of constant macroscopic forces. During polymer flooding, even with an unchanged pressure gradient, both the direction and magnitude of these microscopic forces are altered. This fundamentally distinguishes the behavior of microscopic forces in polymer flooding from conventional waterflooding. The modification (typically intensification) of microscopic forces acting on oil clusters induces their deformation, alters their morphology, and promotes subsequent residual oil migration (Mikhailov, 1992).

The viscous and elastic properties of fluids govern streamline geometry and the microscopic forces controlling their configuration. Experimental studies at the Daqing Oilfield (China) have demonstrated that polymer solution elasticity exerts a greater influence on microscopic streamline patterns than viscosity. Consequently, research predominantly focuses on the impact of polymer fluid elasticity on oil displacement efficiency (Yan et al., 2022; Song et al., 2022).

Core flooding experiments revealed that viscoelastic polymer solutions improve oil displacement efficiency and reduce residual oil saturation through viscoelastic fluid effects, namely the Weissenberg effect induced by polymer chain stretching and the expansion of viscoelastic polymer jets in pore spaces due to the first normal stress difference (Wang et al., 2001).

The impact of elasticity in polyacrylamide (PAM) solutions (molecular weight:  $1.8 \times 10^7$ ) and capillary number on oil displacement efficiency was analyzed in weakly oleophilic homogeneous synthetic cores (oil wettability index: 0.64, water wettability index: 0.4), as shown in Figure 5 (Wu, Wang, 2011).

All three experimental trials (Figs. 5a, b, c) demonstrate that polymer solution elasticity enhances oil displacement efficiency and decreases residual oil saturation across a wide range of capillary numbers.

### Surfactant-Polymer (SP) Flooding

Surfactant-polymer (SP) flooding is a foundational chemical enhanced oil recovery (EOR) method applied

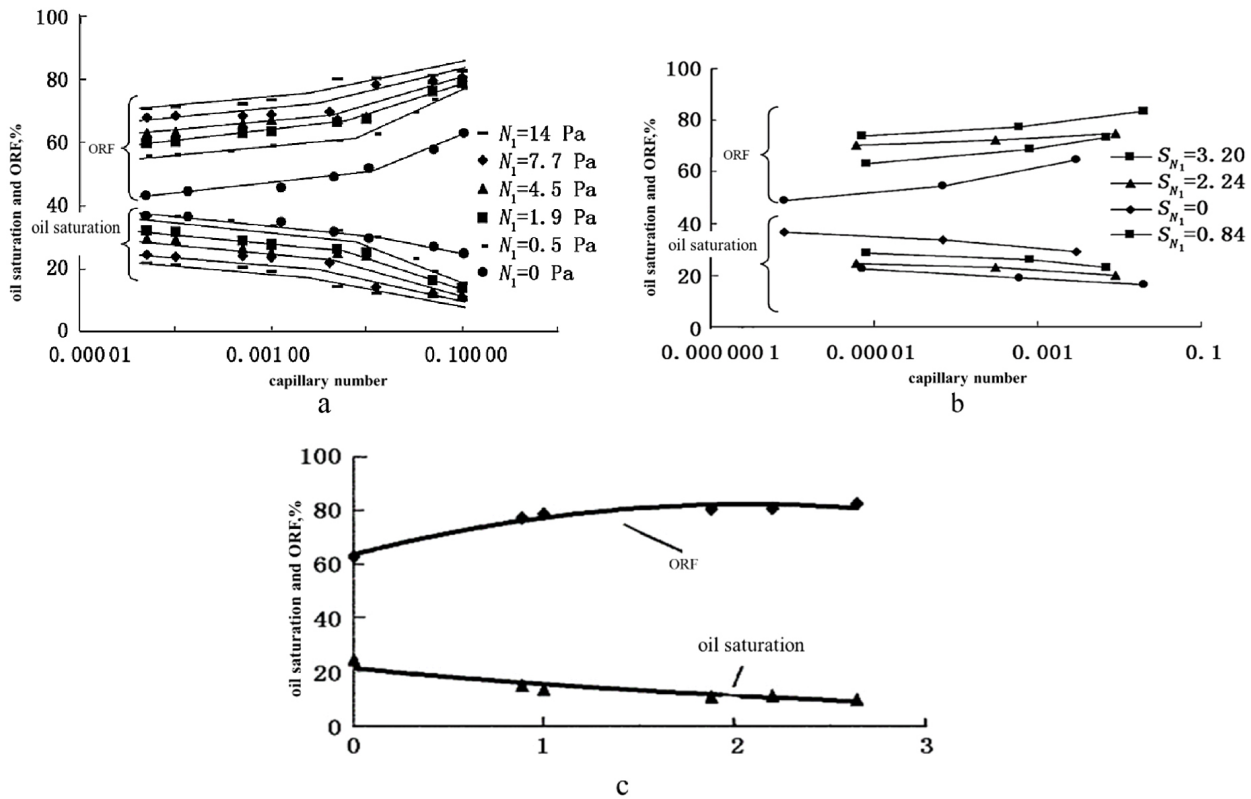


Fig. 5. Effect of polyacrylamide (PAA) elasticity and capillary number (or Weissenberg number) on oil recovery factor (ORF) and residual oil saturation: solution elasticity is characterized by: a – the first difference in normal stresses ( $N_1$ ); b – the slope of the ratio between the first normal stress and the shear rate  $S_{N_1}$ ; c – the Weissenberg number

in large-scale oil fields. The standard implementation involves injecting a polymer-surfactant mixture into the reservoir at a controlled rate. In this process, polymers enhance sweep efficiency by improving mobility control, while surfactants increase displacement efficiency and overall oil recovery. During the preparation of SP solutions, component interactions inevitably alter the fluid’s physicochemical properties.

In oil displacement from heterogeneous reservoirs, the oil recovery factor increases with polymer solution viscosity. Beyond a specific viscosity threshold, the rate of recovery factor growth stabilizes, indicating the existence of a critical viscosity. Conventional flooding requires reducing interfacial tension (IFT) to  $10^{-3}$  mN/m for optimal displacement (Chatzis, Morrow, 1984; Foster, 1973). However, achieving such ultralow IFT values is often physically unattainable or economically unfeasible in most reservoirs. In SP flooding systems, synergistic polymer-surfactant interactions enable optimal oil recovery without requiring ultralow IFT conditions (An et al., 2022).

The effect of capillary number on oil recovery during SP flooding in heterogeneous reservoirs was investigated through laboratory experiments. Polyacrylamide (PAM) was selected as the polymer, while the surfactant system comprised potassium persulfate (KPS) and the anionic-nonionic surfactant YG210-10 (Li et al., 2014) (Fig. 6).

The diagram presented in Figure 6 demonstrates that for heterogeneous reservoirs, the recovery factor map exhibits two distinct characteristic regions. According to classical capillary number theory (formula 1), an increase in the viscosity of the displacing phase or a decrease in interfacial tension (i.e., an increase in the capillary number) leads to a higher displacement efficiency. However, an interesting observation emerges: the capillary number corresponding to Region II is typically higher than that in Region I. Despite this,

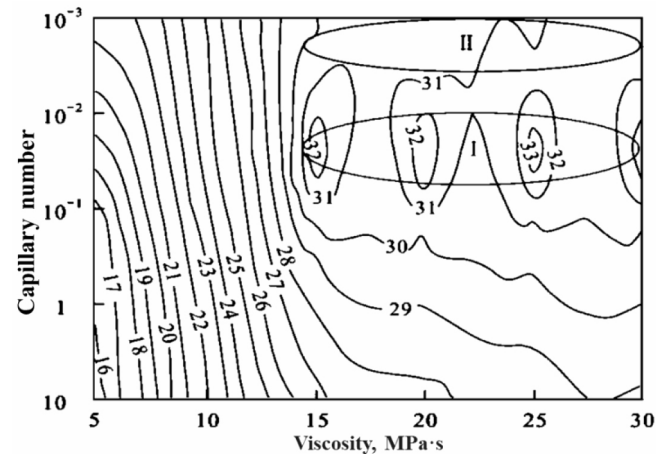


Fig. 6. Map of the ORF increment in the surfactant-polymer flooding system

the resulting recovery factor increment in Region II is somewhat lower compared to Region I. This finding leads to a crucial conclusion: achieving maximum capillary numbers in a heterogeneous reservoir does not necessarily result in the highest recovery factor for residual oil. Consequently, it does not translate into optimal added economic value. This observation challenges the assumption that higher capillary numbers always correlate with better oil recovery performance in heterogeneous reservoir environments.

Figure 7 demonstrates that the maximum increment in the oil recovery factor (ORF) is achieved when the capillary number reaches  $10^{-2}$ . At this capillary number, with viscosity values of 15, 20, 25, and 30 mPa·s, the ORF increment shows minimal variation. Furthermore, at a capillary number of approximately  $10^{-2}$  and viscosities of 15, 20, 25, and 30 mPa·s, the increase in the oil recovery factor is negligible. Considering the composition cost, when the viscosity is 15 mPa·s, the interfacial tension is  $1.865 \times 10^{-2}$  mN/m, and the corresponding capillary number is  $1.975 \times 10^{-2}$ , the oil displacement effect is optimal. Therefore, this capillary number value can be considered the most efficient.

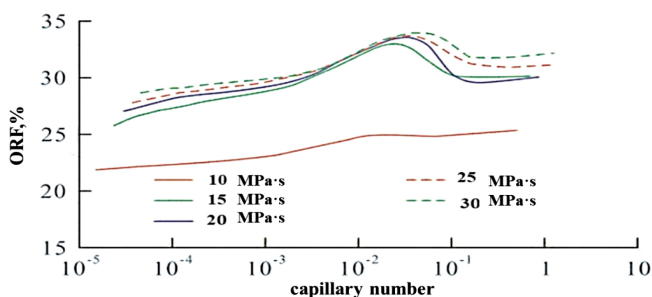


Fig. 7. Relationship between capillary number and recovery factor increment in a surfactant-polymer flooding system

### Alkaline-Surfactant-Polymer (ASP) Flooding

The ASP flooding technology (alkaline-surfactant-polymer flooding) is a type of oil recovery technology that utilizes a complex chemical flooding system consisting of alkali, surfactant, and polymer to enhance oil recovery. The effect is achieved through increased viscosity of the displacing fluid, enhanced displacement volume, and reduced interfacial tension between oil and water. The technology's essence lies in replacing more expensive surfactants with cheaper alkali, which reduces the required amount and loss of surfactants and polymers. Additionally, the alkali reacts with organic acids in crude oil to form oil acid soap, which increases the content of surfactants and further improves oil displacement efficiency (Xu, 2019; Ji, 2012).

Polymer alkali solution cations reduce polymer viscosity through charge screening at the phase interface.

Furthermore, alkali promotes hydrolysis of the amide group in the polymer chain, increasing the negative charge within the molecular chain and enhancing electrostatic repulsion between and within molecules. Consequently, the polymer molecular chain transitions from a more coiled to an extended state, increasing the polymer solution viscosity. The charge screening effect is considered to play a dominant role in these processes (Li et al., 2012).

Figure 8 presents a comparison of residual oil saturation depending on the capillary number for three different ASP systems (Fig. 8a) and shows the relationship between oil recovery and capillary number (Fig. 8b). According to rheological properties, the glycerol system is classified as a viscous system, while the HPAM and xanthan gum systems are classified as viscoelastic systems. The curves in Figure 8 demonstrate that the displacement efficiency for the alkali-surfactant-HPAM system is the highest among the three systems considered. The difference in displacement efficiencies between the two different viscoelastic systems is small, while the glycerol system's displacement efficiency is higher. This indicates that, for polymer systems, elasticity contributes significantly to enhanced oil recovery and reduced residual oil saturation, in addition to viscosity. Comparing the inflection points on the three curves (Fig. 8b) shows that the capillary number at the inflection point for the alkali-surfactant-HPAM system is minimal. This demonstrates that the alkali-surfactant-HPAM system has higher viscoelasticity and, consequently, a higher recovery factor (Jiang, 2004).

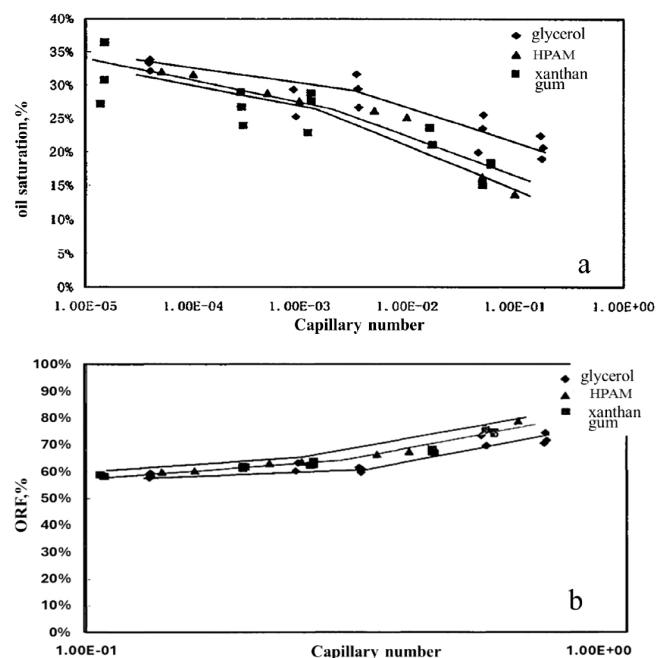


Fig. 8. Capillary displacement curve for various ASP systems (alkali-NaOH, surfactant-ORS41, polymers: glycerin/HPAM/xanthan gum)

## Conclusions

1. During conventional waterflooding, three distinct regimes of residual oil saturation formation have been identified: capillary, capillary-pressure, and self-similar regimes. Two critical capillary number values (mobilization threshold and displacement threshold) separating these regimes have been determined. These thresholds vary with changes in the reservoir's filtration-capacity and surface properties.

2. In chemical flooding processes, reduction of residual oil saturation and increase in displacement efficiency are achieved through capillary number growth.

3. Capillary displacement curves for different chemical flooding technologies exhibit unique characteristics, each having a specific inflection point that indicates minimal residual oil saturation without reaching maximum capillary number values.

4. Additional recovery of residual oil can be achieved within a certain range of capillary numbers even if ultralow interfacial tension values are not attained, through increasing surfactant concentration.

5. The factors of increasing the efficiency of pre-displacement of residual oil from the reservoir during polymer flooding are revealed: the Weissenberg effect and the expansion of the polymer volume due to the first difference in normal stresses.

6. High oil recovery in polymer-surfactant flooding can be achieved without reaching ultralow interfacial tension due to the synergistic effect of polymer-surfactant interaction. An optimal capillary number exists under these conditions.

7. The maximum technological effect of ASP flooding is achieved as a result of the synergistic effect of increasing the viscosity of the displacing liquid, reducing the interfacial tension between the phases and, as a result, increasing the volume of oil being displaced, and its quantification is performed using the formulas presented in the studies (Shakhverdiev and Mandrik, 2007; Shakhverdiev, 2014; Azizaga and Shakhverdiev, 2024), which remained out of the authors' attention.

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## Влияние капиллярного числа на изменение остаточного нефтенасыщения при химическом заводнении

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Представлены экспериментальные результаты изучения кривых капиллярного вытеснения при химических методах повышения нефтеотдачи. Проведён анализ теории капиллярного числа и изменений этого параметра при химических методах повышения нефтеотдачи. Проанализированы результаты исследований кривых капиллярного вытеснения и выявлены общие закономерности и особенности поведения этих кривых в различных экспериментальных условиях. Анализ показал, что при изменении смачиваемости пласта, пористости, проницаемости и поровой структуры кривые капиллярного вытеснения изменяются. В изменяющихся пластовых условиях классические кривые капиллярного вытеснения, ранее полученные в ходе базовых экспериментов, не позволяют осуществлять прогноз остаточной нефтенасыщенности, и кроме того, максимальная нефтеотдача не соответствует максимальным значениям капиллярных чисел. В практике разработки нефтяных месторождений, как правило, нет необходимости в использовании высоких концентраций поверхностно-активных веществ для снижения поверхностного натяжения до сверхнизкого уровня. Добавление полимера и щелочи (в соответствующей концентрации) обеспечивает высокое нефтеизвле-

чение за счёт взаимодействия поверхностно-активных веществ, полимера и щелочи. В настоящее время в Китае технологии ASP заводнения (alkaline-surfactant-polymer flooding – щёлочное заводнение и совместное применение щелочи, ПАВ и полимера) является наиболее эффективным методом повышения нефтеотдачи на заводнённых нефтяных месторождениях и даёт хорошие результаты. Поэтому необходимо исследовать микромеханизмы подвижности и фильтрации остаточной нефти. Исследования кривой капиллярного вытеснения, с учётом структуры коллектора и его базовых фильтрационных характеристик, имеют определяющее значение при разработке нефтяных месторождений Китая, также эти кривые могут быть использованы в мировой практике в качестве основы для повышения нефтеотдачи с помощью третичных методов.

**Ключевые слова:** кривая капиллярного вытеснения, МУН, капиллярное число, сверхнизкое межфазное натяжение

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