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INVESTIGATION OF THE INFLUENCE OF NANOPARTICLE COMPOSITES ON OIL DISPLACEMENT EFFICIENCY

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Abstract. *Introduction.* Development of effective, cheap and environmentally friendly methods for increasing oil recovery of reservoirs is one of the relevant problems of the oil industry all over the world due to the decrease in the extraction of oil due to the decline in reservoir energy. In this regard, various methods of increasing oil recovery in the fields are applied, including gas flooding. Enhanced oil recovery (EOR) techniques play a crucial role in maximizing oil production from reservoirs. *The purpose of this work* to investigate the integration of nanoparticles which has gained significant attention due to their potential to address challenges associated with traditional EOR methods. *Discussion.* The paper focuses on the fundamentals and application of surfactants and nanoparticle mixtures for enhancing oil recovery through CO_2 flooding. One of the key challenges when using CO_2 to increase oil production is controlling gas mobility. *Conclusion.* In this paper, the potential of using surfactants and a mixture of surfactants with nanoparticles to create a stable foam that reduces gas mobility and increases oil production is investigated.

Key words: enhanced oil recovery, nanoparticles, foam, surfactants, CO_2 flooding, interfacial tension, sol-gel method, polymers, dilational rheology

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1. Introduction

The oil industry faces two important challenges: enhanced oil recovery (EOR) and environmental protection. The effects of petroleum products on soil, water and air require special attention. A key factor in process optimization is the study of the physical and chemical properties of petroleum emulsions and soil dispersions. In this context, it is important to consider the effects of surfactants, polymers, alkalines and nanoparticles. Modern materials science is actively engaged in the development of new nanodisperse materials. The study of the formation of surface-active adsorption layers at the interface of phases, as well as picketing emulsions, is important for the prediction and development of effective EOR methods.

Injecting carbon dioxide (CO_2) into oil reservoirs has emerged as a promising technique for enhanced oil recovery (EOR). Not only does this approach enhance oil production, but it also contributes to mitigating climate change by sequestering CO_2 underground. However, one of the significant challenges faced by CO_2 injection projects is mobility control. High CO_2 mobility can lead to unfavorable and unsuccessful outcomes.

The study by Yousef at al. (2020) investigates the ability of this novel approach to generate stable foam in porous media, even at extreme conditions such as supercritical CO_2 (sc-CO_2) and high temperatures. Coreflood experiments demonstrate that the use of surfactants and surfactant-nanoparticle mixtures significantly improves oil recovery compared to traditional methods. The addition of nanoparticles to surfactants further enhances recovery rates, making this approach a promising avenue for efficient EOR [1].

Nanotechnology has emerged as a promising tool for EOR from mature reservoirs. The study by Cheraghian et al. (2020) provides a comprehensive overview of the application of nanotechnology in EOR. The authors discuss the various types of nanomaterials used in EOR, including nanoparticles, nanofluids, and nanoemulsions. They also highlight the different mechanisms by which nanomaterials can improve oil recovery, such as wettability alteration, interfacial tension reduction, and mobility control. The review also addresses the challenges and limitations associated with the use of nanotechnology in EOR, such as high costs, environmental concerns, and the need for further research and development. Overall, the study emphasizes the significant potential of nanotechnology to revolutionize EOR and contribute to sustainable oil production [2].

The use of nanoparticles in EOR has gained significant attention in recent years. The study by Iravani et al. (2023) provides a comprehensive review of the application of nanoparticles for EOR purposes, covering both the history and current challenges. The review highlights the various mechanisms by which nanoparticles can improve oil recovery, including wettability alteration, interfacial tension reduction, and mobility control. The authors also discuss the challenges associated with the use of nanoparticles in EOR, such as nanoparticle stability, transport, and retention in porous media. The review concludes by highlighting the potential of nanoparticles to revolutionize EOR and the need for further research to address the existing challenges and unlock their full potential [3].

In this paper, we delve into surfactant and nanoparticle interactions, explore their industrial applications, and discuss the potential impact on oil recovery.

2. Surface-active properties

A recent study investigated an enhanced foam-flooding system that incorporates nanoparticles and polymers under geological conditions of a reservoir.

2.1 Foam Formulation

The system primarily consists of an anionic foaming agent (CQS-1) and a nonionic surfactant (FH-1). Researchers screened 17 foams based on foaming volumes and foam half-lives. Nanoparticles were selected after evaluating each foam's concentration, the ratio of the main agent to the auxiliary agent, and the foam stabilizer dosage [4].

2.2 Microstructure and Rheological Properties

The selected system's microstructure and rheological properties were analyzed. This included assessing the reservoir's adaptability to temperature resistance, salt tolerance, and adsorption resistance. The study supported the field application of CO_2 foam flooding.

Surface dilational rheology is a critical aspect of foam behavior. It involves determining the surface dilational moduli by observing changes in surface tensions and interface area during bubble sinusoidal oscillation (Hongsheng, et al., 2016). Understanding these properties helps optimize foam stability and performance [5].

Surfactant properties play a key role in the processes of improving oil production using mixtures of surfactants and nanoparticles. Let's look at some aspects related to this topic:

Surface tension: Surfactants reduce the surface tension between oil and water, which contributes to the formation of effective foam systems. This makes it possible to increase the contact between the phases and improve oil production.

Stabilization of foaming: Surfactants and nanoparticles stabilize foaming in the CO_2/water system. This helps to reduce CO_2 mobility and increase oil production.

Research in this area is ongoing, and understanding the surface-active properties of surfactant and nanoparticle mixtures will help develop more effective methods to improve oil production.

2.2.1 Interfacial Tension Reduction

The interfacial tension (IFT) between CO_2 and crude oil is a critical factor influencing the success of CO_2 flooding in enhanced oil recovery (EOR). The injection of CO_2 into a reservoir can lead to a reduction in IFT, promoting better miscibility and mobilization of the trapped oil. The extent of this IFT reduction is significantly influenced by both pressure and temperature, as highlighted in the study by Yang et al. (2015) [6].

The Impact of Pressure

The researchers observed a general trend of decreasing IFT with increasing pressure, which can be attributed to the enhanced solubility of CO_2 in the oil phase at higher pressures. This increased solubility leads to swelling of the oil and a reduction in its viscosity, facilitating its flow through the reservoir. However, the presence of heavy components, such as asphaltenes and resins, in crude oil can hinder this IFT reduction at elevated pressures. The study observed that the IFT reduction rate slowed down considerably at higher pressures, particularly for heavier crude oils. This phenomenon can be attributed to the precipitation of asphaltenes at high pressures, which can adversely affect the interfacial properties and hinder oil recovery.

The Impact of Temperature

Temperature also plays a significant role in influencing IFT. The study revealed that increasing temperature generally leads to a further decrease in IFT. This behavior can be explained by the increased molecular motion and decreased viscosity of the fluids at higher temperatures, which promotes better mixing and interaction between CO_2 and oil.

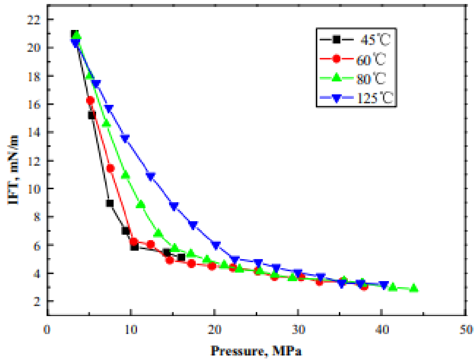

Figure 1 - Interfacial Tension of CO_2 + Crude Oil Systems at Different Temperatures

The figure 1 shows that interfacial tension leads to pressure change for the state of crude oils. In addition, the rate of regulation of interfacial tension is also dependent on temperature, with higher temperatures resulting in a faster initial decrease in interfacial tension.

The study by Alvarado et al. (2010) investigated the interfacial tension (IFT) between CO_2 and reservoir crude oils, as well as CO_2 and hexadecane, under high pressure and temperature conditions. The researchers observed that IFT decreased rapidly with increasing pressure initially. However, as pressure continued to rise, the decrease in IFT slowed down due to the presence of heavy components in the crude oils. The study also highlighted that ultra-low or zero IFT was not achieved in CO_2 + crude oil systems, whereas CO_2 + hexadecane systems exhibited vanishing IFT and miscibility at 318.15K [7].

2.2.2. Adsorption at Interfaces

Surfactants play a crucial role in various applications due to their unique adsorption properties and surface activities. Specifically, when surfactants adsorb at the gas-liquid interface, they form a protective monolayer around gas bubbles. This monolayer acts as a barrier, effectively preventing gas bubble coalescence and drainage (Yang, et al., 2015). The phenomenon of surfactant adsorption at solid/liquid interfaces is also of interest, as it significantly influences the wettability of solid surfaces and provides stability to dispersions of solid particles in liquids [6].

3. Methods of stabilizing CO_2 foam

During CO_2 flooding of oil reservoirs, foam stabilization plays a crucial role. Foam reduces the mobility of injected CO_2, inhibits gas channeling, and improves sweep efficiency. There are several methods of foam stabilization (Hartono, et al., 2024) [8].

3.1 Sol-Gel Method

The stability of CO_2 foam is essential for its effectiveness in various applications, including enhanced oil recovery (EOR) and in-situ carbonation. The study by Ngo et al. (2024) explored the use of a sol-gel method to stabilize CO_2 foam for enhanced in-situ carbonation in foamed fly ash backfill materials. The researchers found that the addition of CO_2 and sodium silicate (SS) to an anionic surfactant solution led to the formation of a stable foam with reduced drainage and strengthened liquid films. The gel network formed by the reaction of SS with CO_2 further enhanced foam stability by adhering to the foam surface. The stabilized foam exhibited improved mechanical properties, making it suitable for use in foamed backfill materials. The enhanced in-situ carbonation achieved with the sol-gel-stabilized CO_2 foam has the potential to improve the strength and durability of backfill materials, contributing to more sustainable mining practices [9].

3.2 Particle/Cationic Surfactant Mixtures

Foam stability is a critical factor in various industrial processes, including enhanced oil recovery (EOR). The study by Amankeldi et al. (2023) investigated the use of surfactant/SiO2 composite nanofluids as foam stabilizers. The researchers examined the effects of different chain lengths and concentrations of the cationic surfactant CTAB (cetyltrimethyl ammonium bromide) on the performance of CTAB-SiO2 nanofluids. The results showed that the addition of SiO2 nanoparticles enhanced foam stability compared to using CTAB alone. The optimal concentration of CTAB for foam stability was found to be 0.5 mM. This study highlights the potential of using surfactant/SiO2 composite nanofluids as effective foam stabilizers in various industrial applications. Figure 2 by Amankeldi et al. (2023) visually demonstrates how the interaction between cationic surfactants and silica particles affects their behavior and, consequently, the stability of the foam. In the absence of surfactants, the particles repel each other due to the negative surface charge. As the surfactant concentration increases, monolayer adsorption occurs, leading to hydrophobic attraction and particle flocculation. A further increase in surfactant concentration leads to the formation of a bilayer and a change in the surface charge of the particles to positive, which causes their redispersion due to electrostatic repulsion [10].

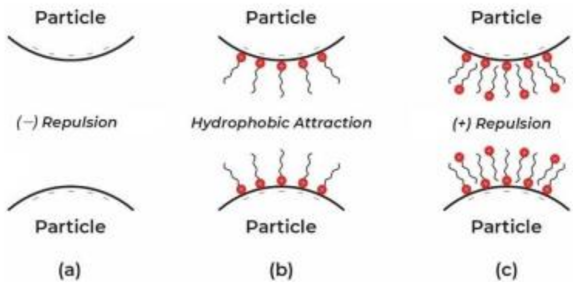

Figure 2 - Microcosmic behavior of two silica particles during different stages of surfactant adsorption: (a) without any adsorption; (b) monolayer adsorption; (c) bilayer adsorption.

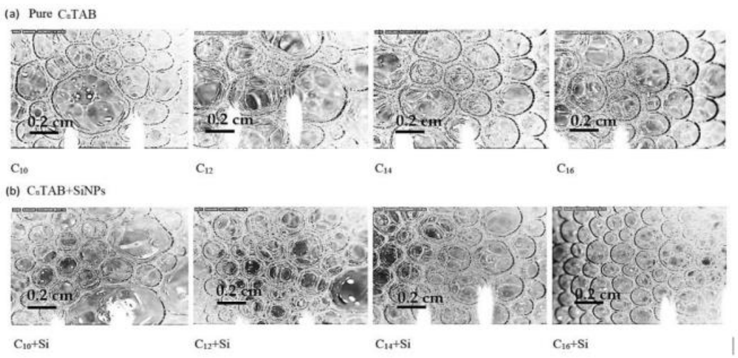

Figure 3 - Morphology of foams generated with (a) pure CnTAB and (b) CnTAB–SiO_2 mixed sol

Figure 3a by Amankeldi, F. et al (2023) shows the foam morphology for the pure surfactants at a concentration of 1×10^{-3} mol/L, taken 10 minutes after foam formation. It was observed that with increasing surfactant chain length, the bubble size decreased and the bubble shape became more spherical. Figure 3b shows that for all CnTAB-SiO2 blends, the bubbles generally appeared more spherical, more uniform and smaller, resulting in an effective packing density without significant bubble deformations [10].

3.3 Nanoparticles and Viscosifiers

Nanocellulose-based Pickering emulsions face a challenge due to the hydrophilic nature of nanocellulose, which prevents effective interactions with the oil phase. However, in research by Agustin et al. (2023) they have found a solution by incorporating lignin nanoparticles (LNPs) as co-stabilizers. These LNPs help decrease oil droplet size and slow creaming, especially at pH 5 and 8, with increasing LNP content. Interestingly, emulsification at pH 3, along with LNP cationization, leads to droplet flocculation and rapid creaming. By adding

LNPs either before or simultaneously with nanocellulose, stability improves due to enhanced interactions with the oil phase. Moreover, these Pickering emulsions can be freeze-dried, resulting in a solid macroporous foam that acts as an adsorbent for pharmaceutical pollutants. This innovative approach offers a green and cost-effective method to stabilize biphasic systems using bio-based nanomaterials without complex modification procedures [11].

4. Stabilization of Foam During CO_2 Flooding Using SiO_2 Nanoparticles

SiO_2 nanoparticles hold significant promise for enhanced oil recovery (EOR) applications. However, their initial surface properties alone are insufficient to play a substantial role in EOR. Recent studies by Iravani et al. (2023), Rizvi et al. (2024), Cheraghian et al. (2020) have demonstrated that functionalizing SiO_2 nanoparticles can significantly enhance their effectiveness in promoting EOR. As a result, there is considerable interest in exploring the application of functionalized SiO_2 nanoparticles in EOR These functionalized nanoparticles exhibit various properties that enable mechanisms such as improved wettability, reduced interfacial tension, enhanced thermal stability, selective plugging, fluid diversion, and catalytic effects [3,12,2].

Engineered nanoparticles have shown great potential in enhancing oil recovery (EOR) due to their unique properties and ability to interact with reservoir fluids and rocks. The study by Ejike and Deumah (2022) provides a concise overview of the application of engineered nanoparticles in EOR. The authors discuss the different types of engineered nanoparticles used in EOR, including silica nanoparticles, metal oxide nanoparticles, and carbon nanotubes. They also highlight the various mechanisms by which engineered nanoparticles can improve oil recovery, such as wettability alteration, interfacial tension reduction, and mobility control. The study also addresses the challenges and opportunities associated with the use of engineered nanoparticles in EOR. The authors emphasize the importance of careful design and selection of nanoparticles to ensure their effectiveness and minimize any potential environmental impacts. Overall, the study provides a valuable overview of the current state of engineered nanoparticle applications in EOR and highlights the potential for further advancements in this field [13].

Another important outcome of the core flooding experiment was the oil recovery factor (RF) during foam flooding. Tables 1 and 2 show recovery factor during SF and NAF flooding to cores (cores 3 and 4) saturated with oil 1 and oil 2, respectively.

Table 1 – Recovery Factor (oil 1)

(no asphaltene)	Cumulative oil produced for SDS	Cumulative oil produced for SDS + NPs	Original oil in place	Recovery factor for SDS	Recovery factor for SDS + NPs
	5 ml	8.10 ml	13.36 ml	37.42 %	60.65 %

Table 2 – Recovery Factor (oil 2)

(high asphaltene)	Cumulative oil produced for SDS	Cumulative oil produced for SDS + NPs	Original oil in place	Recovery factor for SDS	Recovery factor for SDS + NPs
	4 ml	9 ml	13.19 ml	30.33 %	68.23%

The recovery factor increase from approximately 38 % to 61 % demonstrates that the foam flooding technique improved oil recovery, but its efficiency is limited without the destabilizing effect of asphaltenes. The addition of nanoparticles in the foam formulation further increases oil recovery, suggesting that nanoparticles enhance foam stability and mobility control. The recovery factor for oil 2 reached almost 69 %, indicating that nanoparticle-stabilized foam is highly effective for heavy oil with high asphaltene content. The higher recovery factor compared to synthetic oil implies that nanoparticles can counteract the destabilizing effects of asphaltenes and significantly improve foam performance.

Overall, the results underscore the importance of incorporating nanoparticles into surfactant-based foam formulations to optimize oil recovery, particularly in reservoirs with challenging oil compositions. The comparison between the two oils highlights that nanoparticle-enhanced foams can effectively increase the recovery factor by providing better stability and mobility control, even in the presence of high asphaltene content

5. Conclusion

In summary, the application of surfactants and nanoparticles in enhanced oil recovery (EOR) processes holds significant promise. By reducing interfacial tension and enhancing foam stability during CO_2 flooding, these additives improve oil recovery from reservoirs. Key areas of focus include surface-active properties, microstructure, rheological properties, and adsorption at interfaces. Additionally, methods such as the Sol-Gel approach, particle/cationic surfactant mixtures, and SiO_2 nanoparticles contribute to stabilizing CO_2 foam. Understanding the role of polymers in liquid lamellae is crucial for optimizing EOR efficiency. Overall, this research area continues to evolve, offering innovative solutions for sustainable oil production.

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Conflicts of interest: All authors declare that they have no conflict of interest.

НАНОБӨЛШЕК КОМПОЗИТТЕРІНІҢ МҰНАЙЕСЫСУ ТИІМДІЛІГІНЕ ӘСЕРІН ЗЕРТТЕУ

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Түйіндеме. *Кіріспе.* Мұнай өндіруді арттырудың тиімді, арзан және экологиялық таза әдістерін жасау қабат энергиясының төмендеуіне байланысты мұнай өндіру көлемінің төмендеуіне байланысты дүние жүзіндегі мұнай өнеркәсібінің өзекті мәселелерінің бірі болып табылады. Осыған байланысты кен орындарында мұнайдың берілуін арттыру үшін әртүрлі әдістер қолданылады, соның ішінде газ тасқыны. Мұнай өндірудің жетілдірілген әдістері қабаттардан мұнай өндіруді барынша арттыруда маңызды рөл атқарады. *Бұл жұмыстың мақсаты* мұнай өндірудің дәстүрлі жақсартылған әдістерімен байланысты мәселелерді шешуге әлеуетінің арқасында үлкен назар аударылған нанобөлшектерді пайдалануды зерттеу болып табылады. *Талқылау.* Бұл мақалада CO_2 тасқыны арқылы мұнайды жақсарту үшін беттік белсенді заттар мен нанобөлшек қоспаларының негіздері мен қолданылуы талқыланады. Мұнайдың берілуін арттыру үшін CO_2 пайдаланудағы негізгі қиындықтардың бірі газдың қозғалғыштығын бақылау болып табылады. *Қорытынды.* Бұл құжат газдың қозғалғыштығын төмендететін және мұнайдың берілуін арттыратын тұрақты көбік жасау үшін беттік-белсенді заттар мен БАЗ-нанобөлшек қоспаларын пайдалану әлеуетін зерттейді.

Түйін сөздер: жақсартылған мұнай беру, нанобөлшектер, көбік, беттік белсенді заттар, CO2 тасқыны, фазааралық керілу, золь-гель әдісі, полимерлер, кеңею реологиясы

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ИССЛЕДОВАНИЕ ВЛИЯНИЯ КОМПОЗИТОВ НАНОЧАСТИЦ НА ЭФФЕКТИВНОСТЬ НЕФТЕВЫТЕСНЕНИЯ

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Резюме. *Введение.* Разработка эффективных, дешевых и экологически чистых методов повышения нефтеотдачи пластов является одной из актуальных проблем нефтяной промышленности во всем мире в связи со снижением добычи нефти из-за снижения энергии пласта. В связи с этим применяются различные методы повышения нефтеотдачи на месторождениях, в том числе заводнение пласта газом. Методы повышения нефтеотдачи играют решающую роль в максимизации добычи нефти из пластов. *Целью данной работы* является исследование использования наночастиц, которое привлекло значительное внимание благодаря их потенциалу решения проблем, связанных с традиционными методами повышения нефтеотдачи. *Обсуждение.* В статье рассматриваются основы и применение поверхностно-активных веществ и смесей наночастиц для повышения нефтеотдачи пластов посредством заводнения пласта CO_2. Одной из ключевых проблем при использовании CO_2 для повышения добычи нефти является контроль подвижности газа. *Заключение.* В данной статье исследуется потенциал использования поверхностно-активных веществ и смеси поверхностно-активных веществ с наночастицами для создания устойчивой пены, которая снижает подвижность газа и увеличивает добычу нефти.

Ключевые слова: повышение нефтеотдачи, наночастицы, пена, поверхностно-активные вещества, закачка CO2, межфазное натяжение, золь-гель метод, полимеры, дилатационная реология

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References

1. Al Yousef Z.A., Almobarky M.A., Schechter D.S. Surfactant and a mixture of surfactant and nanoparticles to stabilize CO_2/brine foam, control gas mobility, and enhance oil recovery. *J Petrol Explor Prod Technol*., **2020**, *10*, 439–445. DOI: https://doi.org/10.1007/s13202-019-0695-9
2. Cheraghian G., Rostami S., Afrand M. Nanotechnology in Enhanced Oil Recovery. *Processes*., **2020**, *8*, 1073. DOI: https://doi.org/10.3390/pr8091073
3. Iravani M., Khalilnezhad Z., Khalilnezhad A. A review on application of nanoparticles for EOR purposes: history and current challenges. *J Petrol Explor Prod Technol*., **2023**, *13*, 959–994. DOI: https://doi.org/10.1007/s13202-022-01606-x
4. Liu Y., Zhao F., Niu R., Cao S., Liu L., Song Y. Features of nanoparticle Composite enhanced CO2 foam-flooding systems for low-permeability reservoirs. *Frontiers in Energy Research*., **2022**, Vol.10.- 1060356. DOI: https://doi.org/10.1007/s11743-016-1889-5
5. Liu H., Han P., Sun G., Pan F., Li B., Wang J., Changsen L. Dilational Rheology, Foam, and Core Flow Properties of Alpha Olefin Sulfonate. *J Surf Deter*., **2016**, Vol.20. P. 35-45. DOI: https://doi.org/10.1007/s11743-016-1889-5
6. Yang Z., Liu X., Hua Zh., Ling Y., Li M., Lin M., Dong Zh., Interfacial tension of CO_2 and crude oils under high pressure and Temperature. *Colloid. Surface. Physicochem. Eng. Aspect*., **2015**, Vol.482, 611e616. DOI: https://doi.org/10.1016/j.colsurfa.2015.05.058
7. Alvarado V., Manrique E. Enhanced Oil Recovery: An Update Review. *Energies*., **2010**, *3*, 1529-1575. DOI: https://doi.org/10.3390/en3091529
8. Hartono K.F., Permadi A.K., Siagian U.W.R. The impacts of CO2 flooding on crude oil stability and recovery performance. *J Petrol Explor Prod Technol*., **2024**, Vol.14–P.107–123. DOI: https://doi.org/10.1007/s13202-023-01699-y

9. Ngo I., Ma L., Zhao Z. Sol–gel-stabilized CO_2 foam for enhanced in-situ carbonation in foamed fly ash backfill materials. *Geomech. Geophys. Geo-energ. Geo-resour*. **2024**, 10, 80 (2024). DOI: https://doi.org/10.1007/s40948-024-00791-9

10. Amankeldi F., Issakhov M., Pourafshary P., Ospanova Z., Gabdullin M., Miller R. Foam Stabilization by Surfactant/SiO2 Composite Nanofluids. *Colloids Interfaces*., **2023,** Vol. 7 – 57. DOI: https://doi.org/10.3390/colloids7030057

11. Agustin M.B., Nematollahi N., Bhattarai M. Lignin nanoparticles as co stabilizers and modifiers of nanocellulose-based Pickering emulsions and foams/ *Cellulose*., **2023**, Vol.30 – P.8955–8971. DOI: https://doi.org/10.1007/s10570-023-05399-y

12. Rizvi S., Nanotechnology Applications in Enhanced Oil Recovery (EOR). *Int J of Sci Res and Man.*, **2024,** Vol.12(06) – P.135-143. DOI: https://doi.org/10.18535/ijsrm/v12i06.c03

13. Ejike C., Deumah S. Engineered Nanoparticles in EOR: A Quick Overview. *Proceedings of the International Field Exploration and Development Conference*. **2021**, DOI: https://doi.org/10.1007/978-981-19-2149-0_514