INVESTIGATION OF CO2-FOAM STABILITY WITH ANIONIC AND NONIONIC SURFCTANTS AT DIFFERENT SALINITIES

NIHAD HAMAD FARAJ ALSHAKSHOUKI

UNIVERSITI TEKNOLOGI MALAYSIA

INVESTIGATION OF CO2-FOAM STABILITY WITH ANIONIC AND NONIONIC SURFCTANTS AT DIFFERENT SALINITIES

NIHAD HAMAD FARAJ ALSHAKSHOUKI

A project report submitted in fulfilmentof the
requirements for the award of the degree of
Master of petroleum engineering

School of Chemical and Energy Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

JULY 2022

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main thesis supervisor, Professor Dr. WAN ROSLI BIN WAN SULAIMAN, for encouragement, guidance, critics and friendship., advices and motivation. Without their continued support and interest, this thesis would not have been the same as presented here.

I am also indebted to Universiti Teknologi Malaysia (UTM) for funding my master study. Librarians at UTM, Cardiff University of Wales and the National University of Singapore also deserve special thanks for their assistance in supplying the relevant literatures.

My fellow postgraduate student should also be recognised for their support. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family member.

ABSTRACT

Gas flooding is one of the most widely applied EOR methods in field applications, but viscous fingering and gravity segregation are the main issues in gas displacing. To mitigate these problems, water alternating gas injection (WAG) has been used. Another useful proposal is applying foams to improve sweep efficiency because of their high viscosity and mobility. Surfactants have historically been used in field applications to reinforce foam. One of the most important tasks in petroleum engineering is the characterization of the properties of the reservoirs for the application of the method that will lead to a greater oil recovery factor. Among the different tertiary recovery methods with great potential for improving the oil recovery factor, foam injection can be mentioned. In this study, comprehensive laboratory research explored the performance of CO2 foam with anionic and nonionic surfactants. The objectives were to determine the critical micellar concentration (CMC) of SDS and TX100 surfactants and to investigate the effect of varying surfactants salinities and ratios on CO2-FOAM stability. The concentrations of SDS and TX100 were considered in a range of (0.01-0.4wt%). Furthermore, the salinities of SDS and TX100 were fixed at (25000, 30000, 35000, 40000, and 45000 ppm) during the stability tests. This study's methodology included several laboratory tests divided into two sections. In the first section, the surface tension of (SDS) and (TX-100) surfactants was measured to estimate CMC. The second section was to consider the behavior of foam stability in various salinity and ratios of surfactant solutions. The results showed that the CMC for SDS and TX100 surfactants was equal to 0.05 and 0.02 wt%, respectively. Moreover, CO2 foam stability can be improved by increasing the salinity of surfactants solution. SDS at 35000 ppm salinity was the best for CO2 foam stability, which was stable for 8 minutes.

ABSTRAK

Banjir gas ialah salah satu kaedah EOR yang paling banyak digunakan dalam aplikasi lapangan, tetapi penjarian likat dan pengasingan graviti adalah isu utama dalam sesaran gas. Untuk mengurangkan masalah ini, suntikan gas berselang-seli air (WAG) telah digunakan. Satu lagi cadangan berguna ialah menggunakan buih untuk meningkatkan kecekapan sapuan kerana kelikatan dan mobiliti yang tinggi. Surfaktan secara sejarah telah digunakan dalam aplikasi lapangan untuk menguatkan buih. Salah satu tugas terpenting dalam kejuruteraan petroleum ialah pencirian sifat-sifat takungan untuk penggunaan kaedah yang akan membawa kepada faktor pemulihan minyak yang lebih besar. Antara kaedah pemulihan tertiari yang berbeza dengan potensi besar untuk meningkatkan faktor pemulihan minyak, suntikan buih boleh disebut. Dalam kajian ini, penyelidikan makmal yang komprehensif meneroka prestasi buih CO2 dengan surfaktan anionik dan bukan ionik. Objektifnya adalah untuk menentukan kepekatan micellar kritikal (CMC) surfaktan SDS dan TX100 dan untuk menyiasat kesan saliniti dan nisbah surfaktan yang berbeza-beza terhadap kestabilan CO2-FOAM. Kepekatan SDS dan TX100 telah dipertimbangkan dalam julat (0.01-0.4wt%). Tambahan pula, kemasinan SDS dan TX100 telah ditetapkan pada (25000, 30000, 35000, 40000, dan 45000 ppm) semasa ujian kestabilan. Metodologi kajian ini merangkumi beberapa ujian makmal yang dibahagikan kepada dua bahagian. Dalam bahagian pertama, tegangan permukaan surfaktan (SDS) dan (TX-100) diukur untuk menganggarkan CMC. Bahagian kedua adalah untuk mempertimbangkan kelakuan kestabilan buih dalam pelbagai kemasinan dan nisbah larutan surfaktan. Keputusan menunjukkan bahawa CMC untuk surfaktan SDS dan TX100 adalah sama dengan 0.05 dan 0.02% berat, masing-masing. Selain itu, kestabilan buih CO2 boleh dipertingkatkan dengan meningkatkan kemasinan larutan surfaktan. SDS pada kemasinan 35000 ppm adalah yang terbaik untuk kestabilan buih CO2, yang stabil selama 18 minit.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CAC	-	Critical Aggregation Concentration
CMC	-	Critical Micelle Concentration
CST	-	Critical Surface Tension
CNC	-	Cellulose Nanocrystal
CTAB	-	Cetyltrimethylammonium Bromide
EOR	-	Enhanced Oil Recovery
GOR	-	Gas to-oil ratio
GEOR	-	Gas Enhanced Oil Recovery
ID	-	Inner Diameter
IFT	-	Interfacial Tension
MMP	-	Minimum Miscibility Pressure
OD	-	outer diameter
RST	-	Rheometer
SDS	-	Sodium Dodecyl Sulphate
SDBS	-	Sodium dodecyl benzene sulfonate

LIST OF SYMBOLS

CO_2	-	Carbon dioxide
CH_4	-	Methane
C_2H_6	-	Ethane
C_3H_8	-	Propane
L	-	Length of capillary
R	-	Radius
N2	-	Nitrogen
ΔP	-	Deferential Pressure

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Primary, secondary, and tertiary processes are the steps in the classic oil recovery process that are used today. To make oil, the fundamental process relies on the expansion of water, crude oil, gas caps, and dissolved gas in reservoirs, all of which release energy when they are heated. The secondary process involves injecting water or an immiscible gas into reservoirs after pressure has been depleted, in order to keep the pressure constant. Due to high interfacial tension and inadequate mobility control, the average recovery efficiency is only one-third of the original oil in place (OOIP) following primary and secondary operations (Wardlaw, 1996). An EOR (enhanced oil recovery) technique uses tertiary chemistry or thermal energy to solve the difficulties of interfacial tension and/or mobility control, which increases the oil recovery efficiency (Lake, 1989).

More than 70% of the world's oil and gas production is via mature field growth, consisting mainly of secondary and tertiary production. The average recovery factor for gas is 70%, while that of oil, it is about 35%. (East African Scholars Publisher) In the tertiary recovery systems, Enhanced Oil Recovery (EOR) technology is often used, in which chemicals that were not initially present in the reservoir are injected to stimulate oil recovery. EUR strategies optimize the economic potential of mature oil fields by increasing oil recovery and extending field life. (Kittisrisawai and Romero-Zerón, 2015). For decades, gas enhanced oil recovery (GEOR) has been commonly used to improve oil recovery from hydrocarbon reservoirs. Researchers have experimented by injecting various forms of gases into reservoirs with the aim of increasing oil extraction. Carbon dioxide (CO_2), nitrogen (N2), methane (CH4), ethane (C2H6), and propane (C3H8) are some of these gases. (Fakher and Imqam, 2020)

This section provides an overview of the most common EOR approaches, such as chemical EOR, miscible flooding, and thermal methods. Polymers are used to control mobility in chemical EOR procedures and surface-active materials to minimise interfacial tension (IFT). Surfactants supplied directly to the injection solution or soaps produced by the interaction of crude oil and the injected alkaline solution can be used as surface-active materials. There are a variety of chemical EOR methods available, such as surfactant flooding; alkaline flooding; polymer flooding, as well as their combination (e.g., alkaline-surfactant-polymer (ASP) flooding) (Rognmo, 2019).

Molecule EOR processes have mechanisms and limitations unique to each chemical. Surfactants can lower water oil's IFT and change rocks' wettability. High cost and retention of surfactants, such as adsorption on rocks, precipitation in highly salted brine, and partition in residual oil, limit their use. Cost-effective chemicals like alkalis can react with crude oil's acid components to produce soap, which reduces the water-interfacial oil's tension (IFT) and the injected surfactant's ability to adsorb (Nelson *et al.*, 1984). The created soap in alkaline flooding can lower IFT to a satisfactory level if the crude oil's soap number is high enough. The alkalis, on the other hand, can still be employed to minimise the adsorption of surfactant (Nelson *et al.*, 1984). Several factors will affect the stability of these materials, including the interfacial properties of the adsorbed layer between the gas and liquid phases, as well as the bulk properties of the liquid films that isolate the bubbles. The interfacial properties of the air/water interface are often dominant for foam stabilization in relatively simple structures, such as foams stabilized by low molecular weight surfactants. (Chen et al., 2017).

Foams are commonly used in the petroleum industry for stimulation therapy. The use of foamed fracturing fluid in the production of low permeability, low pressure, and water-sensitive reservoirs is gaining prominence. Surfactants can be absorbed at the gas-liquid interface, decreasing surface tension and producing foams. (Zhan et al., 2018).Foam can increase both aerial and vertical sweep efficiencies in high permeability zones by increasing gas-effective viscosity and decreasing gas mobility. (Samimi et al., 2020)

Sodium dodecyl sulphate (SDS) has been commonly used as a foaming agent in many fields due to its low cost and strong foaming ability. Foam can eventually come in contact with salts in practical applications, such as when being mixed with seawater to extinguish a fuel fire or in enhanced oil recovery (EOR). Salts were shown in several experiments to have a direct effect on the foaming performance and foam consistency of SDS foams. SDS foam has the highest foamability in four wt% sodium chloride (NaCl) solution (Jiang et al., 2020). NaCl will not improve the foam stability from 2% to 5%. (Samin et al., 2017). Kumar and Mandal (2017) used various combinations of anionic (sodium dodecyl sulphate) as CO_2-foam foaming agents. Some EOR procedures, such as foam chemical EOR and miscible CO2 flooding, are also secondary processes that can be employed to maintain reservoir pressure and boost oil recovery efficiency at the same time.

1.2 Problem Statement

As global demand for oil increases so does its value and this makes more expensive oil extraction techniques more and more viable. Enhanced Oil Recovery (EOR) offers the only viable solution for retrieving anywhere up to 80% of the world's oil reserves. One of the techniques of EOR is foam flooding, which has proven that it can increase the oil recovery of the reservoir. However, many factors can affect the efficiency of the foam flooding. One of the factors is the surfactant concentration used in the foam flooding. It is believed that surfactant concentration will influence the critical micellar concentration (CMC), the foam adsorption and the ultimate oil recovery.

Additionally, a small number of studies have suggested that a surfactant work as stabilise supercritical CO2 foam. To further understand how stabilise surfactant foam, researchers incorporated a surfactant in the experiment. Because of its widespread use in the industry, sodium dodecyl sulphate (SDS) was chosen as the surfactant. It is the stability of the foam sheets that determines the stability of foam in porous media (lamellae). As a defoaming agent, oil may have an impact on foam performance by decreasing lamellae stability.

Foam has a low density, a high apparent viscosity, and a high blocking capability in high-permeability formations. As a result, foam increases oil recovery by growing sweep efficiency in gas injection, decreasing gas mobility, and redirecting the gas flow. Because of their important properties, foams have been of considerable practical importance, and their use has gained wider acceptance in the petroleum industry. Foam is a two-phase system that includes gas bubbles in a thin liquid film, effectively controls gas mobility, and improves sweeping performance. (Li et al., 2020a).

Foam is a possible alternative to mitigate the above-mentioned gas flood problems. By increasing the apparent gas viscosity and trapping a wide gas fraction within the porous medium, it can significantly decrease gas mobility by many orders of magnitude. In the past, many field experiments were conducted, for example, steam-foam injections, foam-assisted water-alternating gas, carbohydrate spam injections, and foam inundations with a carbon dioxide-solution surfactant used to boost spraying performance. Surfactants have historically been used in field applications to reinforce foam. Although, under extreme pressures of a reservoir such as high temperatures, high salinity, and crude oil contact, penetration enhancer foams are not quite steady. Other considerations such as compressive adsorption of rock matrix, crude oil surfactant partitioning, thermal degradation of a surfactant at the high-temperature further challenge the economic implementation of foam flooding. (Singh and Mohanty, 2017).It is necessary to figure out how foam perform when exposed to oil. Because these foams are used in EOR, their stability must be maintained even when exposed to oil. As a result, it is critical to conduct studies that examine the consequences of oil contact while the three phases are present.

1.3 Objectives of the Study

Thus, the specific objectives of this study are as follows:

I. To estimate the critical micellar concentration (CMC) of SDS and TX100 surfactants.

II. To investigate the effects of varying brine salinities on CO_2 – foam stability.

1.4 Scope of the Study

The scope of the research covers parameter that affects the foam.

I. The CMC of SDS and TX100 were determined in a range of (0.01-0.45wt%).

II. The salinity of SDS and TX100 were determined at (25000, 30000 35000, 40000, and 45000 ppm).

III. Comparison of CO2-foam stability with different salinities.

IV. The experiments were conducted at room temperature 25C and atmospheric pressure 14.7 psi.

1.5 Significance of Study

This work is interesting in that the renewable and organic resource foam has been taken into account. Where foams are used in an enhanced oil recovery as a surface-active agent. In comparison to surfactants and nanoparticles that are commonly used in foam flooding, the foam will become an out-of-box” future technology for enhancing oil recovery. This will serve as the point of departure for further research involving various foam types and altering or incorporating additional materials to enhance moisture and foam consistency to increase foam efficiency in oils and gas industry applications.

REFERENCES

AFZALI, S., REZAEI, N. & ZENDEHBOUDI, S. 2018. A comprehensive review on enhanced oil recovery by water alternating gas (WAG) injection. *Fuel,* 227**,** 218-246.

ALCORN, Z. P., FERNØ, M. A. & GRAUE, A. Upscaling CO Foam for EOR as CCUS from On-To Offshore. Offshore Technology Conference, 2020. Offshore Technology Conference.

ALI, J. A., KOLO, K., MANSHAD, A. K. & MOHAMMADI, A. H. 2018. Recent advances in application of nanotechnology in chemical enhanced oil recovery: Effects of nanoparticles on wettability alteration, interfacial tension reduction, and flooding. *Egyptian journal of petroleum,* 27**,** 1371-1383.

ALMUBARAK, M., ALYOUSEF, Z., ALMAJID, M., ALMUBARAK, T. & NG, J. H. Enhancing Foam Stability Through a Combination of Surfactant and Nanoparticles. Abu Dhabi International Petroleum Exhibition & Conference, 2020. Society of Petroleum Engineers.

ALWADANI, N. & FATEHI, P. 2018. Synthetic and lignin-based surfactants: Challenges and opportunities. *Carbon Resources Conversion,* 1**,** 126-138.

AUDEBERT, A., BEAUFILS, S., LECHEVALIER, V., LE FLOCH-FOUÉRÉ, C., SAINT-JALMES, A. & PEZENNEC, S. 2019. How foam stability against drainage is affected by conditions of prior whey protein powder storage and dry-heating: A multidimensional experimental approach. *Journal of Food Engineering,* 242**,** 153-162.

BABAMAHMOUDI, S. & RIAHI, S. 2018. Application of nano particle for enhancement of foam stability in the presence of crude oil: Experimental investigation. *Journal of Molecular Liquids,* 264**,** 499-509.

BASHIR, A., HADDAD, A. S. & RAFATI, R. 2019. Nanoparticle/polymer-enhanced alpha olefin sulfonate solution for foam generation in the presence of oil phase at high temperature conditions. *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 582**,** 123875.

BELHAJ, A. F., ELRAIES, K. A., ALNARABIJI, M. S., SHUHLI, J. A., MAHMOOD, S. M. & ERN, L. W. 2019. Experimental investigation of surfactant partitioning in pre-CMC and post-CMC regimes for enhanced oil recovery application. *Energies,* 12**,** 2319.

BIKERMAN, J. J. 2013. *Foams*, Springer Science & Business Media.

BRICEÑO-AHUMADA, Z. & LANGEVIN, D. 2017. On the influence of surfactant on the coarsening of aqueous foams. *Advances in colloid and interface science,* 244**,** 124-131.

CAI, B., SAITO, A. & IKEDA, S. 2018. Maillard conjugation of sodium alginate to whey protein for enhanced resistance to surfactant-induced competitive displacement from air–water interfaces. *Journal of agricultural and food chemistry,* 66**,** 704-710.

CAO, Y., XIONG, Y. L., CAO, Y. & TRUE, A. D. 2018. Interfacial properties of whey protein foams as influenced by preheating and phenolic binding at neutral pH. *Food Hydrocolloids,* 82**,** 379-387.

CARPENA, P., AGUIAR, J., BERNAOLA-GALVÁN, P. & CARNERO RUIZ, C. 2002. Problems associated with the treatment of conductivity− concentration data in surfactant solutions: simulations and experiments. *Langmuir,* 18**,** 6054-6058.

CHEN, M., SALA, G., MEINDERS, M. B., VAN VALENBERG, H. J., VAN DER LINDEN, E. & SAGIS, L. M. 2017. Interfacial properties, thin film stability and foam stability of casein micelle dispersions. *Colloids and Surfaces B: Biointerfaces,* 149**,** 56-63.

CHEN, S., LIU, H., YANG, J., ZHOU, Y. & ZHANG, J. 2019. Bulk foam stability and rheological behavior of aqueous foams prepared by clay particles and alpha olefin sulfonate. *Journal of Molecular Liquids,* 291**,** 111250.

CHEN, W. & SCHECHTER, D. S. 2021. Surfactant selection for enhanced oil recovery based on surfactant molecular structure in unconventional liquid reservoirs. *Journal of Petroleum Science and Engineering,* 196**,** 107702.

CHEN, Y., NARAYAN, S. & DUTCHER, C. S. 2020. Phase-dependent surfactant transport on the microscale: interfacial tension and droplet coalescence. *Langmuir,* 36**,** 14904-14923.

DENG, B., DE RUITER, J. & SCHROËN, K. 2019. Application of Microfluidics in the Production and analysis of food foams. *Foods,* 8**,** 476.

DIMITROVA, L. M., PETKOV, P. V., KRALCHEVSKY, P. A., STOYANOV, S. D. & PELAN, E. G. 2017. Production and characterization of stable foams with fine bubbles from solutions of hydrophobin HFBII and its mixtures with other proteins. *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 521**,** 92-104.

DU, D.-J., PU, W.-F., JIN, F.-Y. & LIU, R. 2020. Experimental study on EOR by CO2 huff-n-puff and CO2 flooding in tight conglomerate reservoirs with pore scale. *Chemical Engineering Research and Design,* 156**,** 425-432.

EAST AFRICAN SCHOLARS PUBLISHER, K.

FAKHER, S. & IMQAM, A. 2020. A simplified method for experimentally quantifying crude oil swelling during immiscible carbon dioxide injection. *Journal of Petroleum Exploration and Production Technology***,** 1-12.

FARAJZADEH, R., EFTEKHARI, A. A., DAFNOMILIS, G., LAKE, L. & BRUINING, J. 2020. On the sustainability of CO2 storage through CO2–Enhanced oil recovery. *Applied Energy,* 261**,** 114467.

FU, C. & LIU, N. 2020. Study of the Synergistic Effect of the Nanoparticle-Surfactant-Polymer System on CO2 Foam Apparent Viscosity and Stability at High Pressure and Temperature. *Energy & Fuels,* 34**,** 13707-13716.

GBADAMOSI, A. O., KIWALABYE, J., JUNIN, R. & AUGUSTINE, A. 2018. A review of gas enhanced oil recovery schemes used in the North Sea. *Journal of Petroleum Exploration and Production Technology,* 8**,** 1373-1387.

GHOSH, S., RAY, A. & PRAMANIK, N. 2020. Self-assembly of surfactants: An overview on general aspects of amphiphiles. *Biophysical Chemistry***,** 106429.

GOVINDU, A., AHMED, R., SHAH, S. & AMANI, M. 2019. Stability of foams in pipe and annulus. *Journal of Petroleum Science and Engineering,* 180**,** 594-604.

GUANHUA, N., QIAN, S., MENG, X., HUI, W., YUHANG, X., WEIMIN, C. & GANG, W. 2019. Effect of NaCl-SDS compound solution on the wettability and functional groups of coal. *Fuel,* 257**,** 116077.

JAŃCZUK, B. & ZDZIENNICKA, A. 2019. Critical micelle concentration, composition and thermodynamic properties of n-octyl-β-d-glucopyranoside and sodium dodecylsulfate mixed micelles. *Journal of Molecular Liquids,* 286**,** 110748.

JIANG, J., ZHANG, Z., ZHAO, J. & LIU, Y. 2018. The effect of non-covalent interaction of chlorogenic acid with whey protein and casein on physicochemical and radical-scavenging activity of in vitro protein digests. *Food chemistry,* 268**,** 334-341.

JIANG, N., YU, X., SHENG, Y., ZONG, R., LI, C. & LU, S. 2020. Role of salts in performance of foam stabilized with sodium dodecyl sulfate. *Chemical Engineering Science,* 216**,** 115474.

KILARA, A. & VAGHELA, M. 2018. Whey proteins. *Proteins in food processing.* Elsevier.

KITTISRISAWAI, S. & ROMERO-ZERÓN, L. B. 2015. Complexation of Surfactant/β-Cyclodextrin to Inhibit Surfactant Adsorption onto Sand, Kaolin, and Shale for Applications in Enhanced Oil Recovery Processes. Part II: Dynamic Adsorption Analysis. *Journal of surfactants and detergents,* 18**,** 783-795.

KONG, D., LI, Y., YU, M., MA, R., GUO, H., PENG, Y., XU, S. & YAN, H. 2019. Experimental investigation on block and transport characteristics of foam in porous media for enhanced oil recovery processes. *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 570**,** 22-31.

KUMAR, S. & MANDAL, A. 2017. Investigation on stabilization of CO2 foam by ionic and nonionic surfactants in presence of different additives for application in enhanced oil recovery. *Applied Surface Science,* 420**,** 9-20.

KUTZLI, I., GIBIS, M., BAIER, S. K. & WEISS, J. 2019. Electrospinning of whey and soy protein mixed with maltodextrin–Influence of protein type and ratio on the production and morphology of fibers. *Food hydrocolloids,* 93**,** 206-214.

KWAK, D.-H. & KIM, J.-K. 2017. Techno-economic evaluation of CO2 enhanced oil recovery (EOR) with the optimization of CO2 supply. *International Journal of Greenhouse Gas Control,* 58**,** 169-184.

LI, S., LI, Z. & WANG, P. 2016. Experimental study of the stabilization of CO2 foam by sodium dodecyl sulfate and hydrophobic nanoparticles. *Industrial & Engineering Chemistry Research,* 55**,** 1243-1253.

LI, S., WANG, Q., ZHANG, K. & LI, Z. 2020a. Monitoring of CO2 and CO2 oil-based foam flooding processes in fractured low-permeability cores using nuclear magnetic resonance (NMR). *Fuel,* 263**,** 116648.

LI, X., MURRAY, B. S., YANG, Y. & SARKAR, A. 2020b. Egg white protein microgels as aqueous Pickering foam stabilizers: Bubble stability and interfacial properties. *Food Hydrocolloids,* 98**,** 105292.

LI, X., SARSENBEKULY, B., YANG, H., HUANG, Z., JIANG, H., KANG, X., LI, M., KANG, W. & LUO, P. 2020c. Rheological behavior of a wormlike micelle and an amphiphilic polymer combination for enhanced oil recovery. *Physics of Fluids,* 32**,** 073105.

MARTÍNEZ-BALBUENA, L., ARTEAGA-JIMÉNEZ, A., HERNÁNDEZ-ZAPATA, E. & MÁRQUEZ-BELTRÁN, C. 2017. Applicability of the Gibbs Adsorption Isotherm to the analysis of experimental surface-tension data for ionic and nonionic surfactants. *Advances in colloid and interface science,* 247**,** 178-184.

MONJEZI, K., MOHAMMADI, M. & KHAZ'ALI, A. R. 2020. Stabilizing CO2 foams using APTES surface-modified nanosilica: Foamability, foaminess, foam stability, and transport in oil-wet fractured porous media. *Journal of Molecular Liquids,* 311**,** 113043.

MORADI, B., POURAFSHARY, P., JALALI, F., MOHAMMADI, M. & EMADI, M. 2015. Experimental study of water-based nanofluid alternating gas injection as a novel enhanced oil-recovery method in oil-wet carbonate reservoirs. *Journal of Natural Gas Science and Engineering,* 27**,** 64-73.

MYERS, D. 2020. *Surfactant science and technology*, John Wiley & Sons.

NARSIMHAN, G. & XIANG, N. 2018. Role of proteins on formation, drainage, and stability of liquid food foams. *Annual review of food science and technology,* 9**,** 45-63.

NI, G., LI, Z. & XIE, H. 2018. The mechanism and relief method of the coal seam water blocking effect (WBE) based on the surfactants. *Powder Technology,* 323**,** 60-68.

NIRAULA, T. P., SHAH, S. K., CHATTERJEE, S. K. & BHATTARAI, A. 2018. Effect of methanol on the surface tension and viscosity of sodiumdodecyl sulfate (SDS) in aqueous medium at 298.15–323.15 K. *Karbala International Journal of Modern Science,* 4**,** 26-34.

NORWOOD, E.-A., LE FLOCH-FOUÉRÉ, C., BRIARD-BION, V., SCHUCK, P., CROGUENNEC, T. & JEANTET, R. 2016. Structural markers of the evolution of whey protein isolate powder during aging and effects on foaming properties. *Journal of dairy science,* 99**,** 5265-5272.

OLAYIWOLA, S. O. & DEJAM, M. 2019. Mathematical modelling of surface tension of nanoparticles in electrolyte solutions. *Chemical Engineering Science,* 197**,** 345-356.

OSEI-BONSU, K., GRASSIA, P. & SHOKRI, N. 2017. Relationship between bulk foam stability, surfactant formulation and oil displacement efficiency in porous media. *Fuel,* 203**,** 403-410.

OSEI-BONSU, K., SHOKRI, N. & GRASSIA, P. 2015. Foam stability in the presence and absence of hydrocarbons: From bubble-to bulk-scale. *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 481**,** 514-526.

PAN, F., ZHANG, Z., ZHANG, X. & DAVARPANAH, A. 2020. Impact of anionic and cationic surfactants interfacial tension on the oil recovery enhancement. *Powder Technology,* 373**,** 93-98.

PARRA, J. G., DOMÍNGUEZ, H., ARAY, Y., IZA, P., ZARATE, X. & SCHOTT, E. 2019. Structural and interfacial properties of the CO2-in-water foams prepared with sodium dodecyl sulfate (SDS): A molecular dynamics simulation study. *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 578**,** 123615.

PHUKAN, R., GOGOI, S. B. & TIWARI, P. 2020. Effects of CO2-foam stability, interfacial tension and surfactant adsorption on oil recovery by alkaline-surfactant-alternated-gas/CO2 flooding. *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 597**,** 124799.

REZAEI, A., DERIKVAND, Z., PARSAEI, R. & IMANIVARNOSFADERANI, M. 2021. Surfactant-silica nanoparticle stabilized N2-foam flooding: A mechanistic study on the effect of surfactant type and temperature. *Journal of Molecular Liquids,* 325**,** 115091.

ROSTAMI, A., EBADI, H., ARABLOO, M., MEYBODI, M. K. & BAHADORI, A. 2017. Toward genetic programming (GP) approach for estimation of hydrocarbon/water interfacial tension. *Journal of Molecular Liquids,* 230**,** 175-189.

SAJJADI, S. A., NASRIANI, H. R., DAILAMI, K. & ALIZADEH, N. 2017. Optimizing volumetric sweep efficiency in water flooding by streamline simulation. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects***,** 1-8.

SAMIMI, F., SAKHAEI, Z. & RIAZI, M. 2020. Impact of pertinent parameters on foam behavior in the entrance region of porous media: mathematical modeling. *Petroleum Science,* 17**,** 1669-1682.

SAMIN, A. M., MANAN, M. A., IDRIS, A. K., YEKEEN, N., SAID, M. & ALGHOL, A. 2017. Protein foam application for enhanced oil recovery. *Journal of Dispersion Science and Technology,* 38**,** 604-609.

SENRA, T. D., CAMPANA-FILHO, S. P. & DESBRIÈRES, J. 2018. Surfactant-polysaccharide complexes based on quaternized chitosan. Characterization and application to emulsion stability. *European Polymer Journal,* 104**,** 128-135.

SHARDT, N., WANG, Y., JIN, Z. & ELLIOTT, J. A. 2021. Surface tension as a function of temperature and composition for a broad range of mixtures. *Chemical Engineering Science,* 230**,** 116095.

SHENG, Y., XUE, M., WANG, Y., ZHAI, X., ZHANG, S., WANG, Q., MA, L., DING, X. & LIU, X. 2021. Aggregation behavior and foam properties of the mixture of hydrocarbon and fluorocarbon surfactants with addition of nanoparticles. *Journal of Molecular Liquids,* 323**,** 115070.

VATANPARAST, H., SAMIEE, A., BAHRAMIAN, A. & JAVADI, A. 2017. Surface behavior of hydrophilic silica nanoparticle-SDS surfactant solutions: I. Effect of nanoparticle concentration on foamability and foam stability. *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 513**,** 430-441.

WANG, L., SUN, N., WANG, Z., HAN, H., YANG, Y., LIU, R., HU, Y., TANG, H. & SUN, W. 2019. Self-assembly of mixed dodecylamine–dodecanol molecules at the air/water interface based on large-scale molecular dynamics. *Journal of Molecular liquids,* 276**,** 867-874.

WANG, Z., ZHANG, S. & VARDHANABHUTI, B. 2015. Foaming properties of whey protein isolate and λ-carrageenan mixed systems. *Journal of food science,* 80**,** N1893-N1902.

WARSI, F., ISLAM, M. R., ALAM, M. S. & ALI, M. 2020. Exploring the effect of hydrophobic ionic liquid on aggregation, micropolarity and microviscosity properties of aqueous SDS solutions. *Journal of Molecular Liquids,* 310**,** 113132.

WOŁOWICZ, A. & STASZAK, K. 2020. Study of surface properties of aqueous solutions of sodium dodecyl sulfate in the presence of hydrochloric acid and heavy metal ions. *Journal of Molecular Liquids,* 299**,** 112170.

XIAO, S., ZENG, Y., VAVRA, E. D., HE, P., PUERTO, M., HIRASAKI, G. J. & BISWAL, S. L. 2018. Destabilization, propagation, and generation of surfactant-stabilized foam during crude oil displacement in heterogeneous model porous media. *Langmuir,* 34**,** 739-749.

XIONG, X., HO, M. T., BHANDARI, B. & BANSAL, N. 2020. Foaming properties of milk protein dispersions at different protein content and casein to whey protein ratios. *International Dairy Journal,* 109**,** 104758.

XU, X., SAEEDI, A. & LIU, K. 2017. An experimental study of combined foam/surfactant polymer (SP) flooding for carbone dioxide-enhanced oil recovery (CO2-EOR). *Journal of Petroleum Science and Engineering,* 149**,** 603-611.

YAO, Y., LUO, Y., XU, Y., WANG, B., LI, J., DENG, H. & LU, H. 2018. Fabrication and characterization of auxetic shape memory composite foams. *Composites Part B: Engineering,* 152**,** 1-7.

YEKEEN, N., IDRIS, A. K., MANAN, M. A. & SAMIN, A. M. 2017a. Experimental study of the influence of silica nanoparticles on the bulk stability of SDS-foam in the presence of oil. *Journal of Dispersion Science and Technology,* 38**,** 416-424.

YEKEEN, N., IDRIS, A. K., MANAN, M. A., SAMIN, A. M., RISAL, A. R. & KUN, T. X. 2017b. Bulk and bubble-scale experimental studies of influence of nanoparticles on foam stability. *Chinese Journal of Chemical Engineering,* 25**,** 347-357.

ZHAN, F., LI, J., WANG, Y., SHI, M., LI, B. & SHENG, F. 2018. Bulk, foam, and interfacial properties of tannic acid/sodium caseinate nanocomplexes. *Journal of agricultural and food chemistry,* 66**,** 6832-6839.
ZHANG, X., ZHENG, W., ZHANG, T., GE, J., JIANG, P. & ZHANG, G. 2019. CO2 in water foam stabilized with CO2-dissolved surfactant at high pressure and high temperature. *Journal of Petroleum Science and Engineering,* 178**,** 930-936.