Correlating the rheological properties of Pickering emulsions with the enhanced oil recovery efficiency in porous media

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SCA051

Introduction

Globally the overall oil recovery efficiency for primary and secondary recovery range from 35% to 45% and tertiary recovery methods that can increase the enhanced oil recovery (EOR) efficiency by 10-30% could contribute to energy supply. The tertiary (EOR) methods are commonly based on the injection of materials to displace the trapped oil. During EOR processes, the physicochemical properties of the rock alter to favor the mobilization of trapped oil ganglia. This might occur with: (i) the reduction of the interfacial tension thus decreasing the capillary forces; (ii) the increase of water viscosity, thus increasing the mobility ratio; (iii) the alteration of the wettability, thus facilitating the detachment of oil from the rock surfaces. Conventional EOR methods include chemical flooding (CEOR), gas injection, thermal recovery, microbial enhanced oil recovery (MEOR), low-salinity waterflooding, and foam-EOR. CEOR includes different methods of injecting polymers, surfactants, salts and alkalis into the reservoirs. Studies have shown that polymer flooding might increase oil recovery by 5-30% of original oil in place (OOIP). Especially, Pickering emulsions have been suggested as substitutes or improvers for traditional polymer surfactants systems, appear superior performance with regard to chemical stability, suitable rheological properties, low-cost, and environmental safety. The use of Pickering emulsions in EOR processes comprise an emerging and well-promising approach.

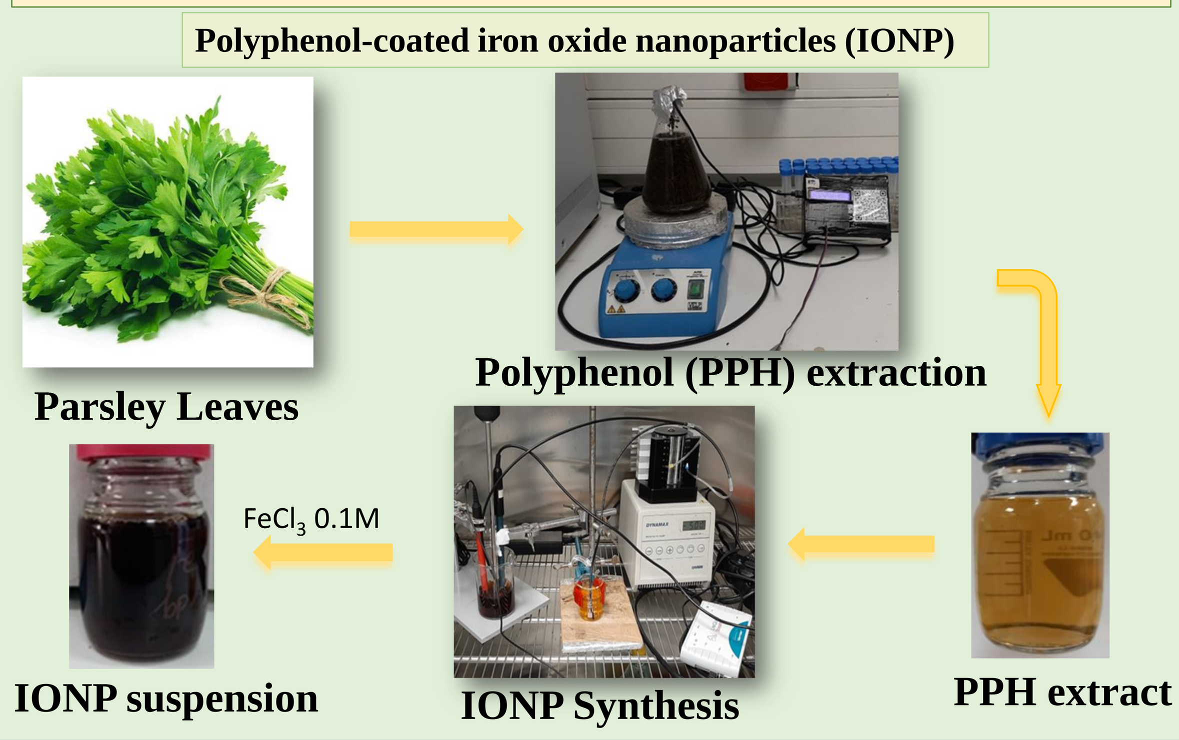
Objectives

- Development of "smart fluids" by grafting adequately synthesized polymers to the surface of nanoparticles, and use them as agents for the synthesis of Pickering emulsions.
- Correlation of the stability / longevity of nano-colloids, and rheological behavior of Pickering emulsions with their composition (salinity, ionic strength, divalent ion concentration, oil to water volume ratio).
- Correlation of the interfacial and rheological properties of "smart fluids" with their capacity to mobilize oil ganglia from porous media (micromodels, sanpacks, core plugs).
- Selection of the most efficient "smart fluids" for EOR processes.

Methodology

Synthesis and stabilization of nano-colloids

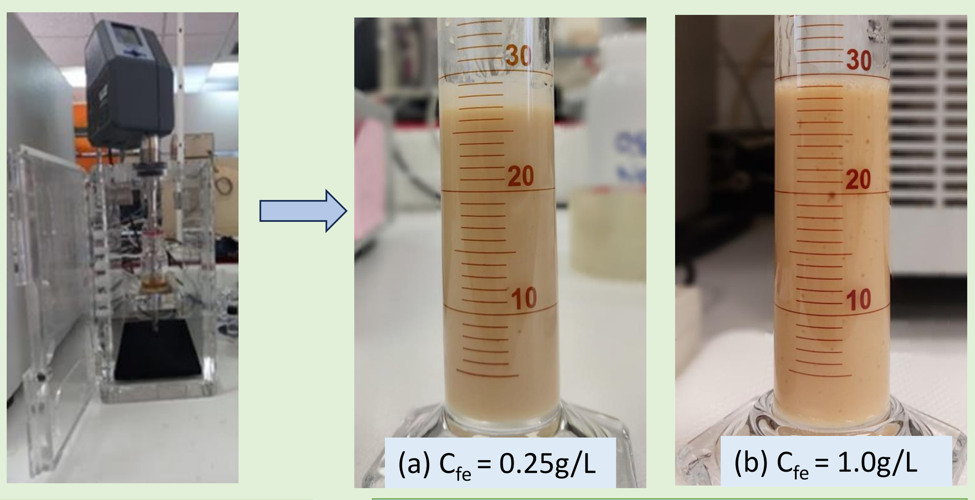
Polyphenol-coated iron oxide nanoparticles (IONP)



Properties of Iron Oxide Nanoparticles (IONP)

	PPHs : pH=6.36 , ζ-potential= -37.7mV IONPs: pH=6.05, ζ-potential =-22.9mV					Displacing suspension in Secondary Imbibition			
Nanoparticle suspension	Surface tension (mN/m)	Interfacial tension (mN/m)	Contact angle air / suspension θ(°)	Contact angle synthetic oil / suspension θ(°)	Average diameter of nanoparticles (nm)	Primary Drainage $^*S_o$	Primary Imbibition S_o	Secondary Imbibition S_o	EOR efficiency (%)
IONPs 1.0g/L	52.89±0.29	53.54	21.7 ± 0.02	9.6± 8.7	141.8±5.8	0.85	0.52	0.50	3.8
IONPs 0.75g/L	54.47±0.41	55.31	25.7 ± 0.20	20.7 ± 5.1	164.2±2.2	0.84	0.511	0.518	-1.4
IONPs 0.5g/L	56.48±0.27	58.12	33.4±2.4	24.9±3.1	105.7±8.2	0.81	0.45	0.45	0.0
IONPs 0.25g/L	59.78±0.17	58.35	25.4±1.20	19.1±0.6	105.7±16.2	0.81	0.53	0.52	1.9
PPHs 3.0g/L	45.29 ± 0.13	49.05	-	-	68.06±8.3	0.82	0.542	0.541	0.2

Pickering Emulsions Synthesis and Properties



Ultrasound probe

IONP stabilized Pickering emulsions

Volume ratio: IONPs suspension – nC$_{10}$ [2:1]

The rheology of Pickering emulsions follows the power law model: $\mu = \mu_{inf} + (\mu_1 - \mu_{inf})\dot{\gamma}^{n-1}$

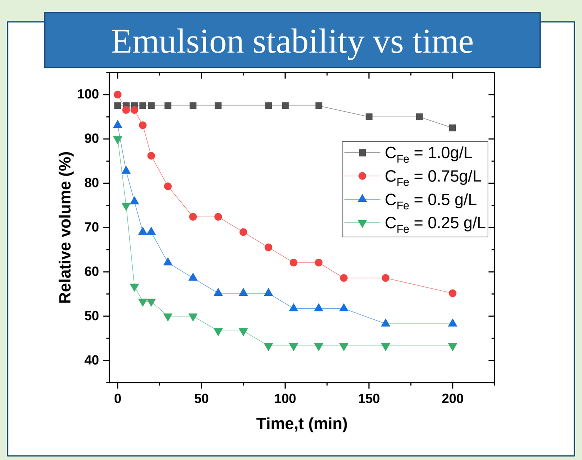
$$\langle\mu\rangle = \mu_{inf} + \left(\frac{\mu_1 - \mu_{inf}}{n}\right)\gamma_w^{\,n-1} \qquad Ca = \frac{u_0 <\mu>}{\gamma_{ow}} \qquad \kappa = \frac{<\mu>}{\mu_{disp}}$$

$$\gamma_w = \left(\frac{8u_p}{4r_H}\right)\left(\frac{3n+1}{4n}\right) \rightarrow u_p = \frac{u_0}{\varphi_V} \rightarrow \varphi_V = \frac{\pi\langle W_p\rangle\langle D_p\rangle}{4L_p^{\,2}}$$

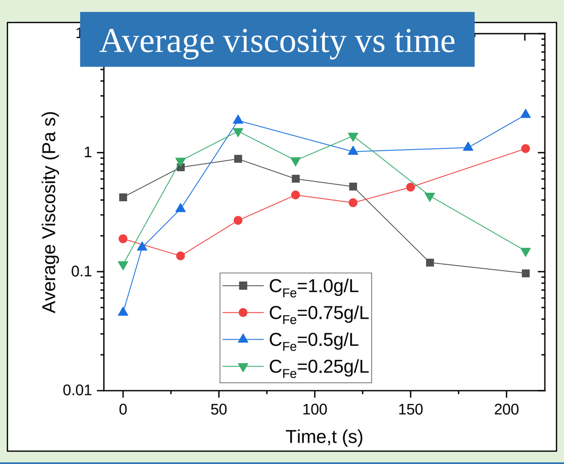
γ_w is the shear rate at pore-wall, φ_V is the porosity of the planar porous medium at the vertical direction, r_H is the equivalent hydraulic pore radius (r_H=45 μm) [3] , Ca capillary number, κ viscosity ratio , μ_{disp} = 0.026 Pa s

Emulsion	μ_1 (Pa s)	μ_{inf} (Pa s)	*n*	<μ> (Pa s)	*Ca* (10^{-5})	κ
C_{Fe} =1.0 g/L	2.468	0.001	0.196	0.423	11.9	1.63
C_{Fe} =0.75 g/L	1.053	0.003	0.217	0.189	5.98	0.72
C_{Fe} =0.5 g/L	0.213	0.006	0.252	0.045	1.37	0.17
C_{Fe}=0.25 g/L	0.564	0.002	0.287	0.115	3.45	0.44

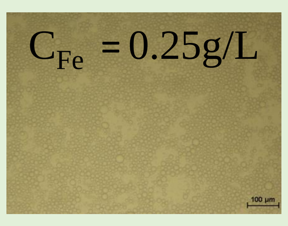
Emulsion stability vs time

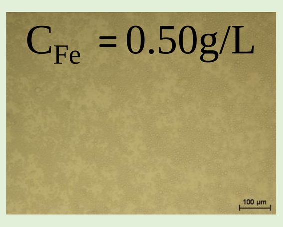


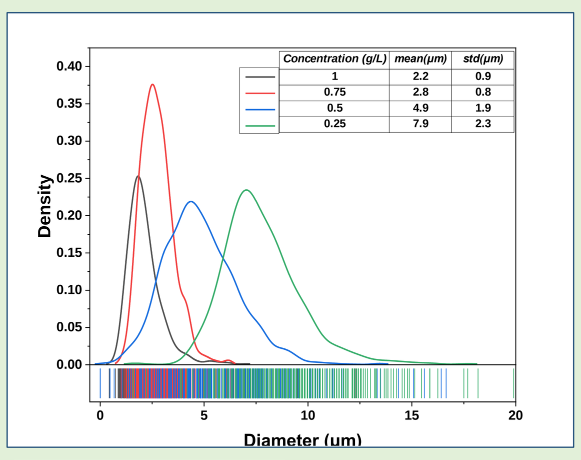
Average viscosity vs time

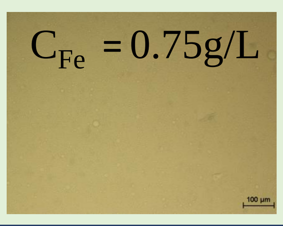


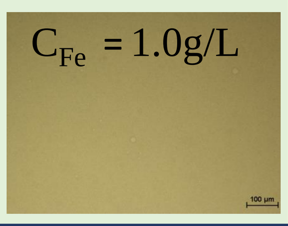
Oil-drop size distributions in emulsions



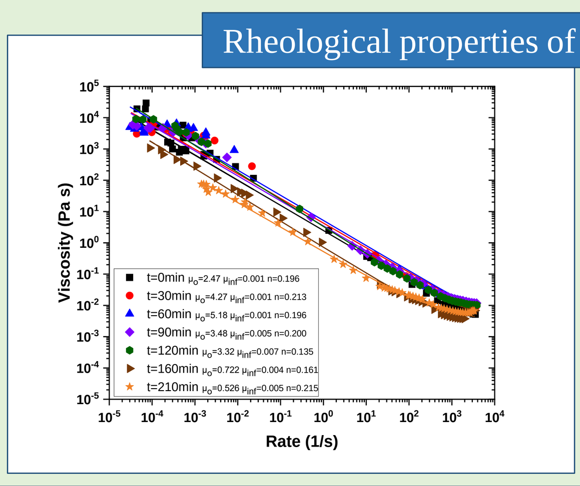


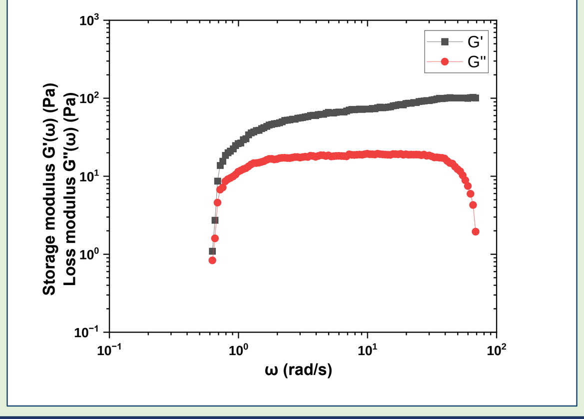




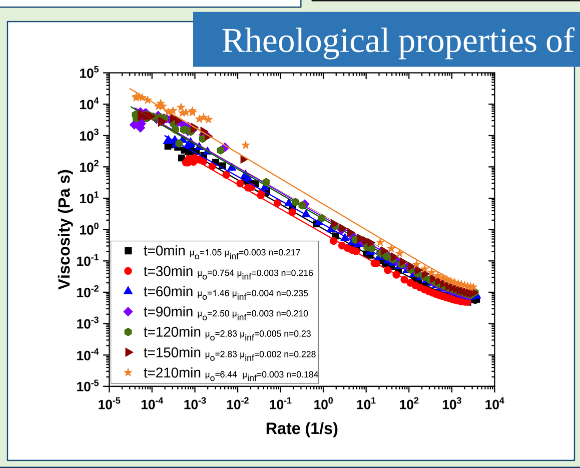


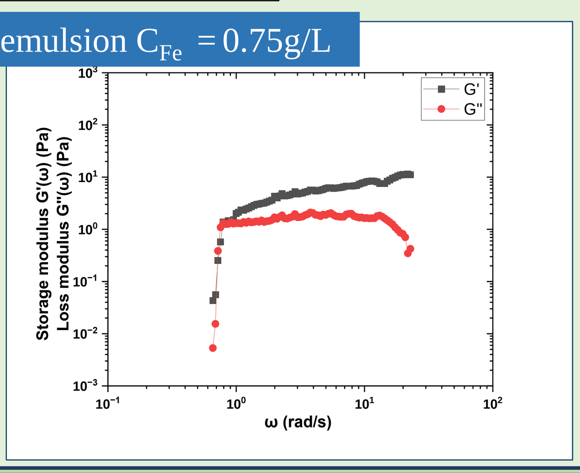
Rheological properties of emulsion C_{Fe} =1.0g/L





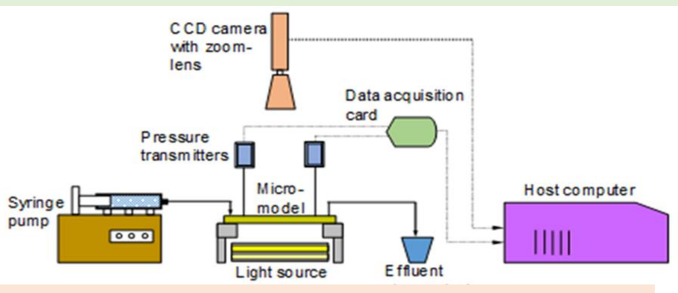
Rheological properties of emulsion C_{Fe} = 0.75g/L



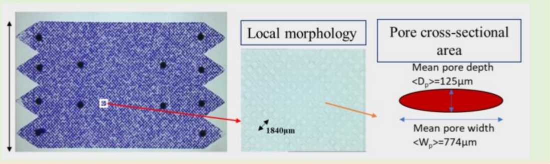


Assessing the EOR efficiency of emulsions

Visualization tests on a transparent pore network

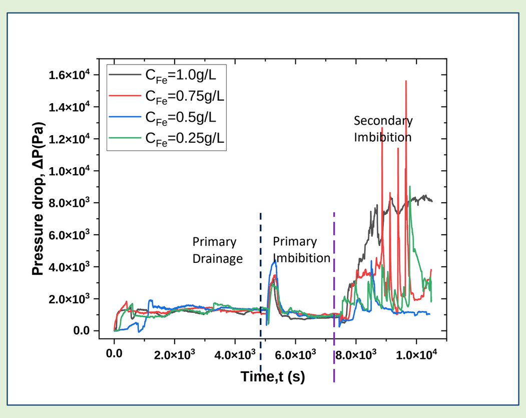


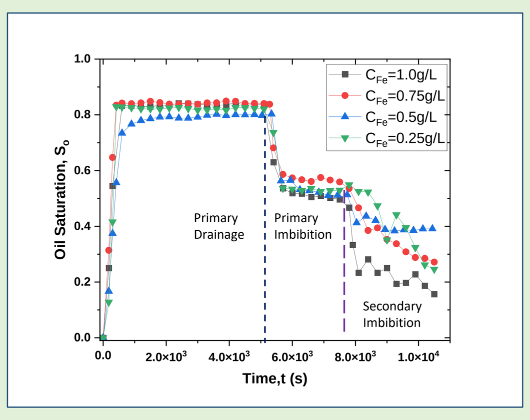
Schematic diagram of experimental setup



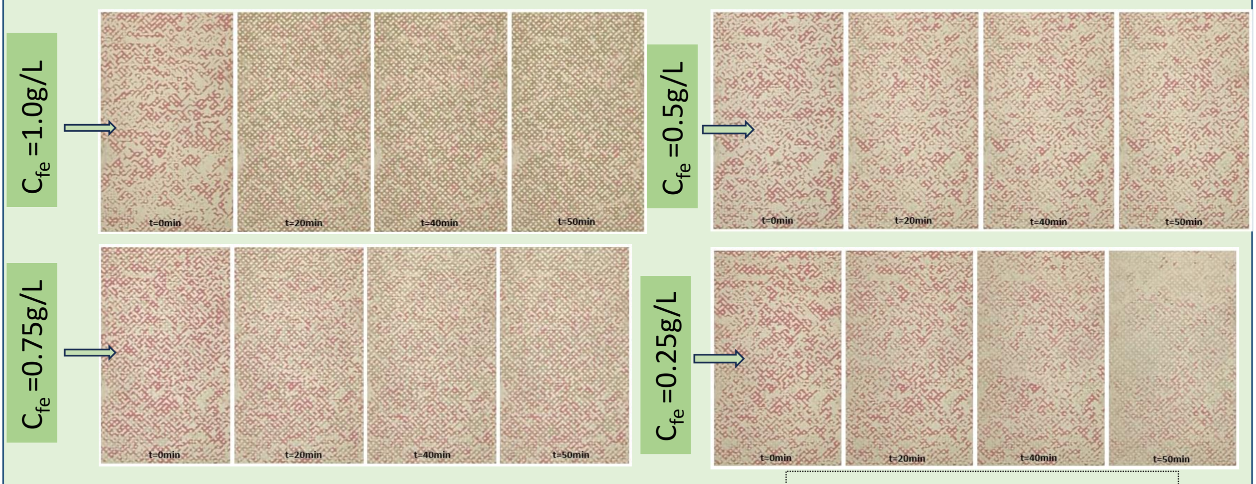
Morphology of glass-etched pore network

Permeability k=20.5 Da
Porosity φ=0.65





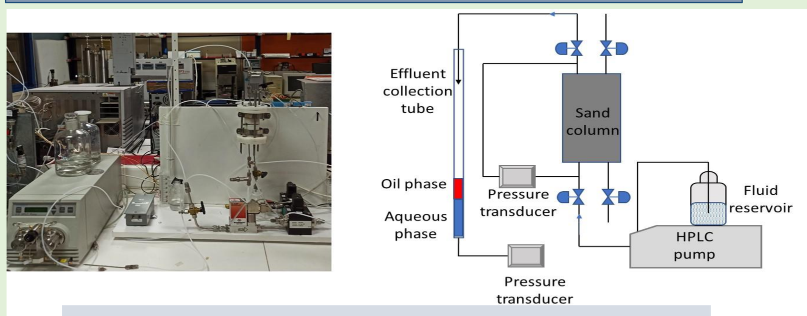
Secondary Imbibition by Pickering Emulsions



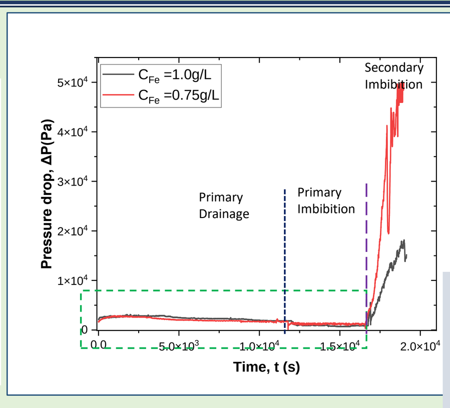
Flow rate at: *Primary Drainage* 0.08mL/min & *Primary/Secondary Imbibition* 0.2mL/min

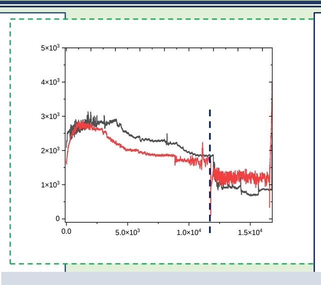
Injected Volume
Primary Drainage 8mL
Primary Imbibition 8mL
Secondary Imbibition 10mL

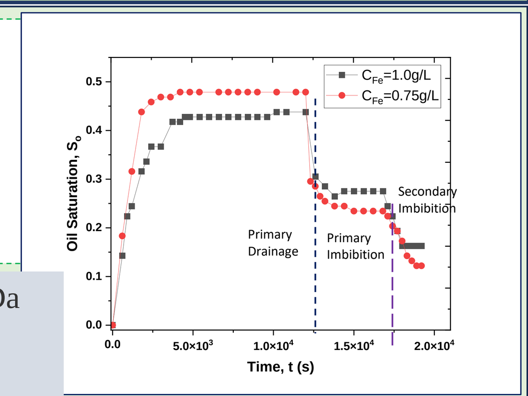
Displacement tests on a sandpack



Schematic diagram of experimental setup







Permeability k=11.9 Da
Diameter=3.0 cm
Length=6.6 cm
Porosity φ=0.49

Flow rate at: *Primary Drainage* 0.4ml/min & *Primary/Secondary Imbibition* 1ml/min

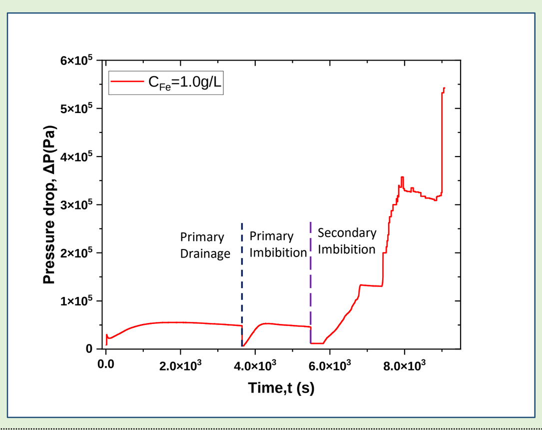
Injected Volume
Primary Drainage 80mL , *Primary Imbibition* 80mL, *Secondary Imbibition* 40mL

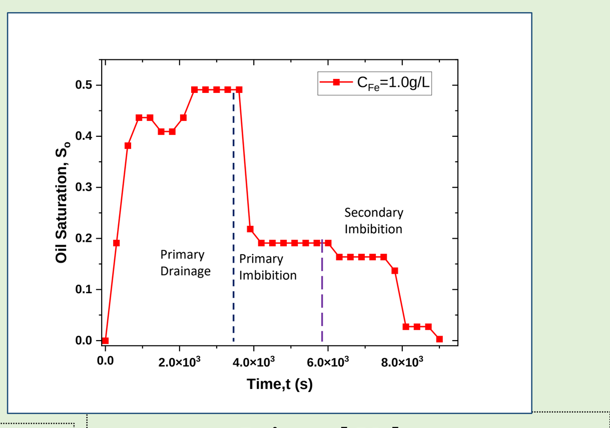
Tests on a core plug of Bentheimer sandstone

Permeability k=0.91 Da
Diameter D=2.52 cm
Length=6.75 cm
Porosity φ=0.219

(a)Core plug

(b)Experimental setup





Flow rate at: *Primary Drainage/Secondary Imbibition* 0.5mL/min & *Primary Imbibition* 1mL/min

Injected Volume
Primary Drainage &
Primary /Secondary Imbibition 30mL

	Displacing **emulsion** in Secondary Imbibition	Primary Drainage $^*S_o$	Primary Imbibition S_o	Secondary Imbibition S_o	EOR efficiency (%)
Glass pore network	*1.0 g/L*	0.83	0.49	0.15	69.4
	0.75g/L	0.84	0.55	0.27	50.9
	0.5g/L	0.80	0.51	0.39	23.5
	0.25g/L	0.82	0.52	0.24	53.8

	Displacing **emulsion** in Secondary Imbibition	Primary Drainage $^*S_o$	Primary Imbibition S_o	Secondary Imbibition S_o	EOR efficiency (%)
Sandpack	*1.0 g/L*	0.44	0.28	0.16	42.8
	0.75g/L	0.48	0.23	0.12	47.8
Core plug	*1.0g/L*	0.49	0.19	0.0	100

$^*S_o$ Residual oil saturation

References

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Acknowledgments

The research project is supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "1st Call for H.F.R.I. Research Projects to support Faculty members and Researchers and the procurement of high-cost research equipment" (Project Number: HFRI-FM17-361, Title: Enhanced oil recovery by polymer-coated nanoparticles, Acronym: EOR-PNP).

Conclusions

- ✓ Polyphenol-coated iron oxide nanoparticles (IONPs) were synthesized and the nano-colloid suspensions were stabilized successfully.
- ✓ The decrease on the interfacial tension and contact angle facilitates the emulsification and detachment of oil ganglia from the solid surface by the nano-colloid suspensions.
- ✓ The EOR efficiency is maximized when using Pickering emulsions, due to the high viscosity ratio, and the creation of stable displacement front.
- ✓ The maximum EOR efficiency is attained by the emulsion prepared at the highest IONP concentration (1.0 g/L), composed of small oil drops of narrow size distribution, and characterized by the lowest viscosity at late times (maximum stability)