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Research Article

Experimental and modelling study of PAM aqueous solution flow to enhance oil recovery

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ABSTRACT

This work studied the effect of polymer on the water flow behavior towards extracting the remain oil from reservoir by polymer flooding method experimentally and numerically. Polymer polyacrylamide PAM of (1000, 1500, 2000 and 2500) ppm were mixed with tap water and brine water separately. Rheological and physical properties of these solutions where performed in usual and porous conditions. Viscosity behavior due to the shear rate, temperature, salt and polymer concentration are tested. Core flooding test used to simulate the flow in porous media and check the pore volume, porosity, permeability, and oil recovery percentage. Ansys– software used to visualize the flow behavior of these solutions on reducing viscous finger in contact zone between injected fluid and crude oil. The results showed that the viscosity of aqueous solutions decreases with the shear rate, temperature, and salt concentrations increasing, while increases with the polymer concentration increasing.Non-Newtonian flow and shear thinning effect associated with the polymer solutions behavior.PH value increases and surface tension increase with the polymer concentration increasing. Oil recovery reach 95% at 2500 ppm of PAM/brine water solution during core test. High stability and less viscous finger effect produced in touching region between polymer solution and crude oil, at this ratio clearly appear as qualitative contour in numerical simulation.

Keywords: - polymer flooding, non- Newtonian flow, viscosity, surface tension, crude oil, core flooding test and numerical simulation.

INTRODUCTION

Crude oil is a complex hydrocarbon component (hydrogen and carbon), salinity or acid was classified according to the level of sulfur that found on it, extracted and pull out crude oil from reservoir was differ for north and south Iraq, later known by high salinity water with crude oil was extracted from well[1].Oil represent backbone of modern life that used in industry, energy etc. However, found problems associated to the amount of oil was remain in reservoir after primary and secondary stages. Three stages were applied to extract crude oil from reservoir[2]. Primary recover~ 15% from Original Oil In Place(OOIP) by pressure was able to pull out reservoir [3]. Secondary stage recover ~ 30% from OOIP by injected external fluids like gas or water to increase pressure within reservoir. Due to macroscopic and microscopic factors lead to still ~ 55% from OOIP in pores of rocks [4]. Chemicals, thermal or gas were injected to obtained further amount from oil after water flooding[5]. On the other hand , In water flooding was need to high amount of water, high different viscosities between water and oil lead to viscous finger was obtained and not has ability to transform wettability from oil-wet to water-wet then lead to unsweep efficiency and lowering oil recovery[6]. Chemicals such as surfactant, alkaline and polymer successful methods for tertiary or enhance oil recovery (EOR) [7].Polymer flooding was able to enhance Macroscopic and Microscopic sweep efficiency. Oil in macroscopic porous media was effected by viscosity of aqueous solution. Increase viscosity lead to decrease mobility ratio of injected fluid by increase concentration dissolved within solution and less formation viscous fingerings and/or channels [8]. Moreover, polymer solution was reduced relative permeability of oil (Kro) less than water relative permeability (Krw) [9]. Elasticity of non-Newtonian fluid that related to viscoelastic phenomena was controlled on microscopic porous media of oil. Therefore, oil remain in closed end was removed[10,11], oil film on rocks was striped it [12-15], prevent oil droplet from broken in oil zone [16] and shear thickening phenomena for injected fluid[17]. Wettability was important petro physical properties that accelerate oil recovery from porous media after water flooding [18]. In petroleum engineering preferred water-wet system in which oil was flowed in free shapeand not connected on rock surface [19]. Oil-wet system in shape of continuous film of oil was connected on rock surface [20].The rheological properties of an injected fluid have an important effect on oil-displacing efficiency in the chemical flooding process [21]. Enhanced rheological behaviors by add polymer which play advantage role in producing less viscous finger in the EOR process [22]. Therefore, it is necessary to investigate the rheological properties of the samples before experimental flooding is measuring.

Modelling of non-Newtonian fluid flow in porous media have more complicated because these related to the ability of one phase to remove another. Furthermore, size, distribution of pores, porosity and permeability. Computational Fluid Dynamic (CFD) were used by[23], studied compared between Newtonian and viscoelastic fluid by design geometry represent stable oil droplet in pore throats, observed pull out trapped oil by viscoelastic fluid in reason of high normal stress; Debora number and imposed force on oil droplet to release it. Finite element method (FEM) based on Galerkin approximation were used by[24], made simulation for laminar multiphase water and oil, designed geometry from circular tube with radius0.05 m and 8m length in Computational Fluid Dynamic (CFD),the result obtained, velocity profile; volume fraction; shear rate; pressure distribution and interfacial thicknesses at different time were showed by COMSOL multiphasic software. Computational Fluid Dynamic (CFD) were used by[25], made simulation of displacement process for multiphase water-oil flow in downward inclined pipe, volume of fluid(VOF) model and refine mesh was used, result obtained, increase inlet water velocity led to high displacement efficiency and instability of interface was caused by increase pipe inclination angle. Simulation of non-Newtonian pseudo plastic fluid by vertical helical coils geometry were designed by[26], used Computational Fluid Dynamic (CFD) in Fluent 6.3,these study based on static pressure at hexahedral and tetrahedral grid; total pressure and velocity magnitude at different angle,they obtained that details inside flow phenomena of the coil. Mathematical model used to simulation polymer flow in porous media by depend on viscosity of polymer were showed by [27],observed that concentration, molecular weight, alkaline, PH and salinity effect on viscosity of hydrolysis polyacrylamide (HPAM).[28] used analytical solution, showed stability in contact region between injected fluid and oil depend on viscosity of solutions which effect on mobility ratio and viscous finger.

In this present work, polyacrylamide (PAM) at different concentrations was mixed with tap and brine water. Rheological, physical and petro physical properties were measured. Experimental flooding was performed to check oil recovery. Computational Fluid Dynamics (CFD) by FLUENT16.1 was used to investigate volume fraction of oil-brine water and oil-polymer aqueous solutions .Two- phase flow through core consider as porous media was used in core flooding test. Volume of Fluid (VOF) approach which including effect of surface tension and viscosity was apply to produce viscous finger difference between brine water and polymer aqueous solution.

Experimental part

Materials and Methods

Polyacrylamide (PAM) with molecular weight ≥ 3000000(g/mol), density (1.182) g/mol and glass transienttemperature (159) C° provided from (china).Tap water , brine water andcrude oil with viscosity (3.115) Cp and density (0.9993) g/cm^3 at 25C° were used. Rock (core) in type of sandstone provide from Nasiriya reservoir cut from depth of (2010.07) m.

Polymer aqueous solution

Brine water was prepared by mixing 20% of Nacl with tap water using magnetic stirrer for 10min. Mixing each (1000, 1500, 2000 and 2500) ppm of PAM with (50) ml tap water and brine water separately. Magnetic stirrer also, used for 30min at 25C° to dissolve PAM added. The tests done after one day.

Rheological Properties Measurement

Brookfield cone - plate viscometer with spindle: 41Z was used to measure rheological properties at different concentrations of polyacrylamide with tap and brine water. Viscosity test due to different shear rate (25-250) S^{-1}, temperature (25-55) C°, brine and polymer concentration. In addition, flow curveat shear rate range (25-250) s^{-1} was obtained.

Physical Properties Measurement

Density

Density test was performed using GP-120 S based on ASTM D-792 from China. The test made with different solutions.

PH

PH was perform using WTW, type Inolab 720. Technical Specification: 4X Alkaline AA, 1,5V. PH range: 2.000 to 19.99. Temperature: -5 to 105 C°. Housing (D) x (H) x (W): 23x8x21, 5cm.

Surface tension

Surface tension was perform using JZYW-200B Automatic Interface Tensiometer provided through BEING UNITED TEST CO., LTD china.Check surface tension of polymer aqueous solutions in tap and brine water at 25C° are made in contact with air.

Petro physical properties

These tests available in Basra Oil Company / Research and Quality department-Nahran Omar.

Porosity

ULTRA PORE 300 makes this test. TEMCO DIV. OF CORE LAB. TULSA, Oklahoma.www.temco.com.

Permeability

The permeability of all solutions and air made using Ultra Perm 550.

Coreflooding test

Preparation core

Corewas cleaned by Soxhlet extraction utilizing toluene and methanol, placed the core in a drying oven for 12 hour to dried it at 100 °C,saturated dried core by brine water, weight after and before saturated, put inside accumulative filled by brine water and weighted again. In this stage can determine pore volume (PV), porosity and permeability for air and liquid. Table2, show that.

Conditioning stage for core

Put core sample inside core holder, same reservoir pressure applied on it, displacement brine water by experimental oil. The purpose from this method to make core with reservoir conditions and calculate irresidual water saturation (Swi) and initial oil saturation (Soi).

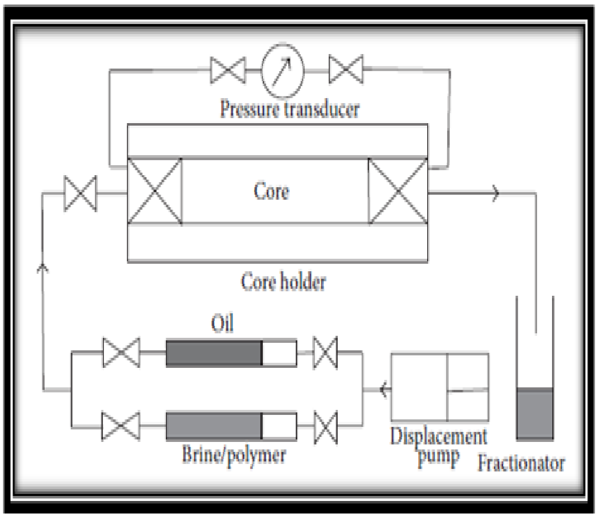


Figure (1): diagram of core flooding schematic[29]

Experimental flooding

In this work experimental flooding washold on two steps to makecompare between brine water without and with (2500) ppm PAM . Firstly, by brine water and secondly, by brine water and when reach to break through point (water cut)inject (2500) ppm brine polymer aqueous solution.Figure1 shows the core flooding schematic.

Flooding carried out by remove oil from core at flow rate (6) cm^3/min derived from average of all south oil reservoir. Magnitude of pressure (1600) Psi related to permeability of core. Flooding continue and calculate time to reach break through point, which represent first drop of water with oil. Displacement continue until water read with total volume equal 99.9%, and then calculate oil recovery. Table (3), show that.

CFD Analysis by FLUENT16.1

Modeling

Figure2 (a), shows the sandstone core used in this study. Geometry consist of 2-D,same dimension of core that used in experimental flooding. Oil is found in core by filled it firstly. Introduced brine water or polymer aqueous solutions from inlet zone.

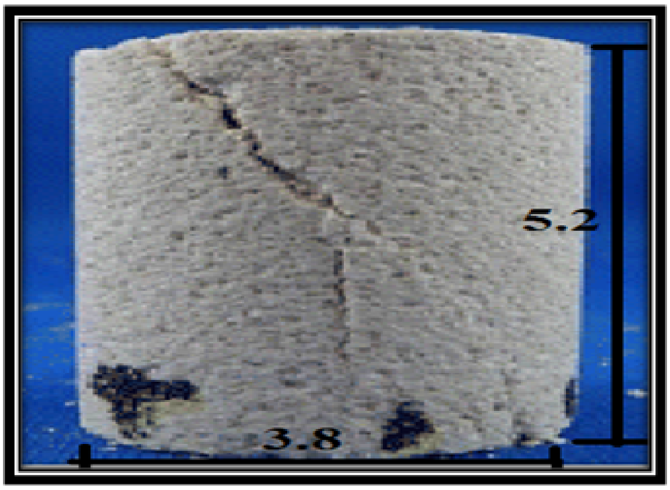
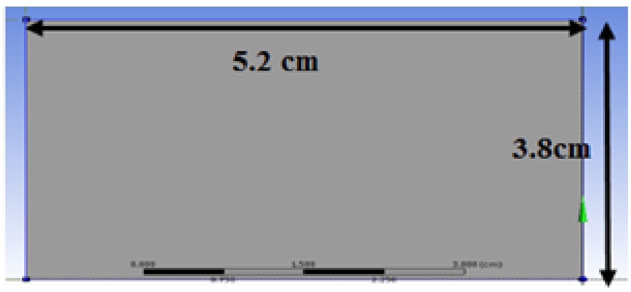


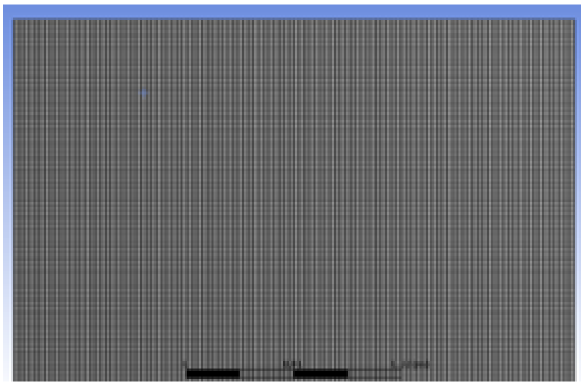
Figure2:- Sandstone core with (5.2) cm length and (3.8) cm diameter

Mesh

Applying mesh to divided the model into number of elements and nodes basic on finite volume method. Mesh is complete by depend on face sizing, body sizing, edge sizing, face meshing and refine .Figure 3(b), show the mesh of 2-D model consist of elements (8800) and nodes (8991).



(a)



(b)

Figure3:- (a)-Geometry of model and (b) Meshing of model

Main Assumptions

A-Steady, laminar flow.

B- Viscosity dependent on shear rate for polymer aqueous solutions but brine water viscosity independent on shear rate.

C- Power law model.

Governing Equations

The governing continuity and momentum equations can be write as,

Continuity equation:

$$\nabla u = 0$$

Where, *u* is the non-Newtonian PAM solution velocity.

Momentum equation:

$$\rho \frac{\partial u}{\partial u} + \rho u.\nabla u - \mu \nabla^2 u - \nabla P$$

For steady non-Newtonian, PAM solution flow, momentum equation is write as,

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - \left(\frac{1}{\rho}\right)\frac{\partial \tau_{xy}}{\partial y}$$

Where, *u* and *v* are the *x* and *y* velocity components respectively, τ_{xy} is the shear stress and ρ is the density of non-Newtonian PAM solution with shear thinning.

Power low model $\mu = k\gamma^{n-1}$

Where $\mu$is the viscosity,*k*is consistency index,$\gamma$is the shear rate and*n*is the power law index.

Boundary conditions

A-Volume Of Fluid (VOF) model is selected with number of phases=2. Then select Implicit of VOF.

B- Viscosity, density, surface tension, n and k taken from experimental data that showed in table1.

C- Operating pressure is set as (101325) and gravity is consider in Y-direction as (-9.81) m/s^2

D- Select(6) cm^3/min flow rate in inlet zone for brine water and polymer aqueous solutions.

E- Wall be stationary and No-slip.

F- Select pressure as outlet.

G-Number of iteration is 50.

Experimental results

Viscosity Curve

Figure 4, shows viscosity curve behavior of (1000, 1500, 2000 and2500) ppm at 25C°.Tap and brine water behave as Newtonian flow without mixing with PAM polymer. Which independent of shear rate. While the non-Newtonian behavior and shear thinning effects increase with the PAM concentrations increasing. The shear viscosity indicates rapid decreasing up to 100 S^{-1} shear rate then the behavior gradually decreasing and attempt to be stable. Shear viscosity increases with PAM concentration increasing.

Moreover, the brine solutions indicate lower viscosity for all concentrations. Gel like formation increase with PAM concentration increasing which decreases mobility ratio. While the viscous finger reduces by increasing the viscosity of PAM aqueous solution.

These results compatable with the boundary conditions of reservoir.

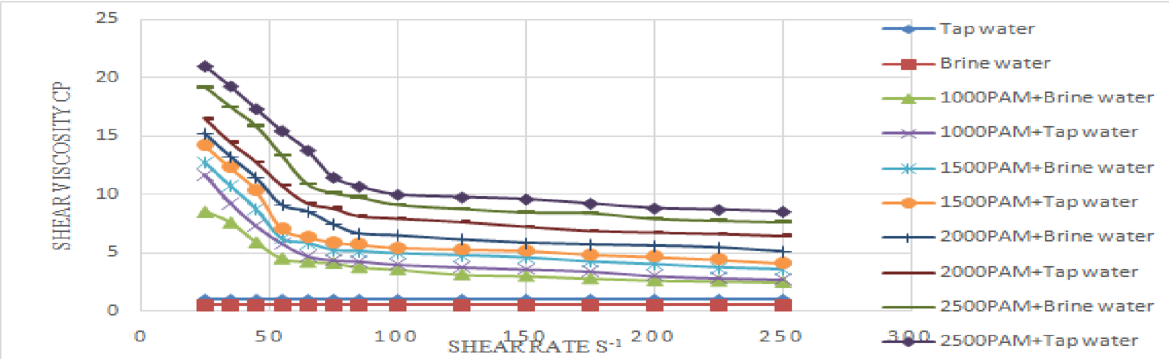


Figure4:- shear viscosity versus shear rate for different PAM aqueous solutions

Flow curve

Figure5, show demonstrates the shear stress increments with shear rate expanding for all PAM aqueous solutions. PAM with brine water indicate lower shear stress than that with tap water. Shear stress attempt to be nonlinear with PAM concentrations increasing because non-Newtonian behavior. (2500) ppm PAM aqueous solutions which is more suitable to use in polymer flooding.

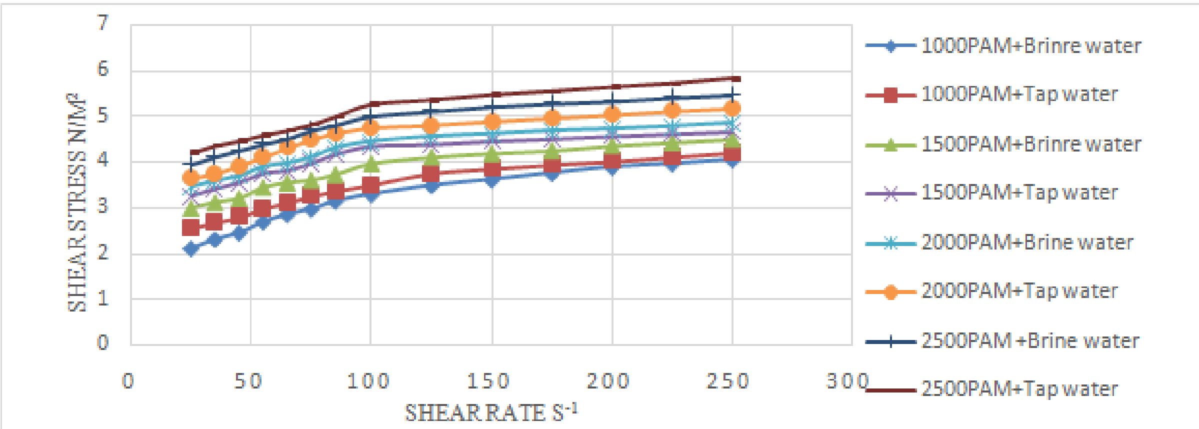


Figure 5:- shear stress against shear rate of different PAM aqueous solutions

Effect of Temperature

Figure6, Indicates approximately constant behavior with temperature increasing for all aqueous solutions. Lower viscosity for PAM with brine as compared in tap water. The different values between brine and tap aqueous solutions reductions with PAM concentration decreasing.

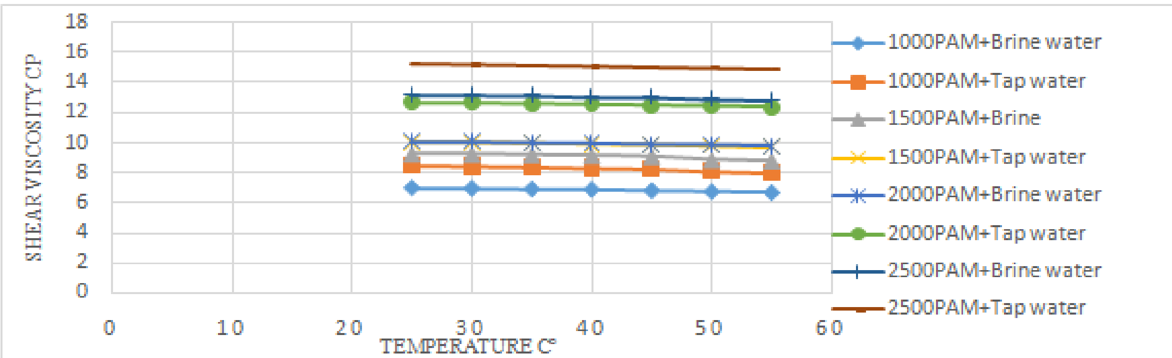


Figure 6:- shear viscosity against temperature of different PAM aqueous solutions at 25 s^{-1}shear rate

Density

Density of polymer aqueous solution increase with (1000, 1500, 2000 and 2500) ppm PAM increasing respectively as show in table 1. High density referred by increase interlink ages between chains.On the other hand dissolved these concentrations by brine water led to lower density compared with the tap water.

PH

Dissolved (1000, 1500, 2000 and 2500) ppm PAM respectively in water increase PH value from neutral to basic with same magnitude for all concentrations. On the other hand, when dissolved these concentrations by brine maintained on constant PH values with same concentrations as show in table1.The PAM/ brine aqueous solutions indicate higher PH values than that with tap water.

Surface Tension

The surface tension increases with the PAM concentration increasing for all solution. While the surface tension of PAM with tap indicate, higher value compared with brine water as show in table 1.The maximum surface tension values obtained for tap and brine aqueous solutions with 2500 ppm tables1 show that.

The power low index n decreases and viscosity consequences K increase with the PAM concentrations increasing for tap and brine solutions. Calculated values for n and K comparable with the non- Newtonian flow behavior and shear thinning effect of PAM aqueous solution. The lower n value the higher shear thinning effect which representing by 2500ppm PAM aqueous solutions. The n and K values are very important data for Ansys program to simulate the flow in porous media in core test.

Table (1):- density, PH, Surface tension for polymer aqueous solutions

Aqueous solution (ppm)	Density (g/cm^3)	PH	Surface tension (mN/m)	Interfacial tension (mN/m)	Power law index (n)	Consistency K (pa .s^2)
oil	0.9993	10	35	-	-	-
Tape water	1.05	7	72	38	-	-
Brine water	0.65	9	20	15	-	-
1000PAM+ tap water	0.98	8	25.8	9.2	0.3283	0.08544
1500 PAM+ tap water	0.9838	8	26.6	8.4	0.2731	0.1308
2000 PAM+ tap water	0.9952	8	27.3	7.7	0.2358	0.23003
2500 PAM+ tap water	0.9979	8	28.5	6.5	0.1434	0.4783
1000PAM+ brine water	0.9791	9	25.1	9.9	0.4657	0.03837
1500 PAM + brine water	0.9799	9	25.5	9.5	0.3593	0.08093
2000 PAM+ brine water	0.9951	9	26.8	8.2	0.2630	0.1746
2500 PAM+ brine water	0.9968	9	27.7	7.3	0.1841	0.3521

Core flooding test

Viscosity increased was applied to EOR by polymer flooding and compared by water flooding. Oil releasefrom sandstone core sample in core flooding by injected brine water and 2500 ppm PAM aqueous solution separately were application. The result of that show in table 3.Injected brine water was accelerate time for reach to break through point and increase water cut magnitudes. Increase brine water injected lead to obtain 99.98% water cut magnitude. Slowly time with decrease water cut values to 99.8% by injected 2500 ppm polymer aqueous solution after break through point. This result agreement with [30], show increase injected solution viscosity was lead to decrease water cut amounts, time and increase oil recovery.The oil recovery amounts about (60.82 and 95) % by brine water and 2500 ppm PAM aqueous solution respectively. Furthermore, additional oil recovery reach about 34.18 % by later solution.This result like [31], which used (2000 and 2500) ppm partial hydrolysis polyacrylamide give (19.21 and 21)% additional oil recovery respectively. Through these results conclusion ability of polymer aqueous solution to enhanced macro and micro sweep efficiency.This result similar to [32], show rheological effects joined with microscopic phenomena that the non-Newtonian solution release oil from both pore throats and pore bodies,macroscopic shared by high oil recovery 56% and development break through time. Also, macroscopic pictures indicated that the pulling and stripping techniques.

Table2:-Pore volume, porosity and permeability

Sample	Pore Volume (%)	Porosity (Ø)	Permeability K (mD) Ka	Kl	Ko
Core	14.76	26.4	50	26.92	7.45

Table3:- Oil Recovery

Sample	Injection solution with Brine Water	Oil Recovery from (OOIP) %	Additional recovery (OOIP) %	Saturation (%) Swi	Soi	Sor
Core	Brine water	60.82at99.98% water cut	-	18.7	81.3	39.18
	(2500) ppm PAM	95at99.8% water cut	34.18			5

Qualitative Numerical Result

Volume Fraction Contour

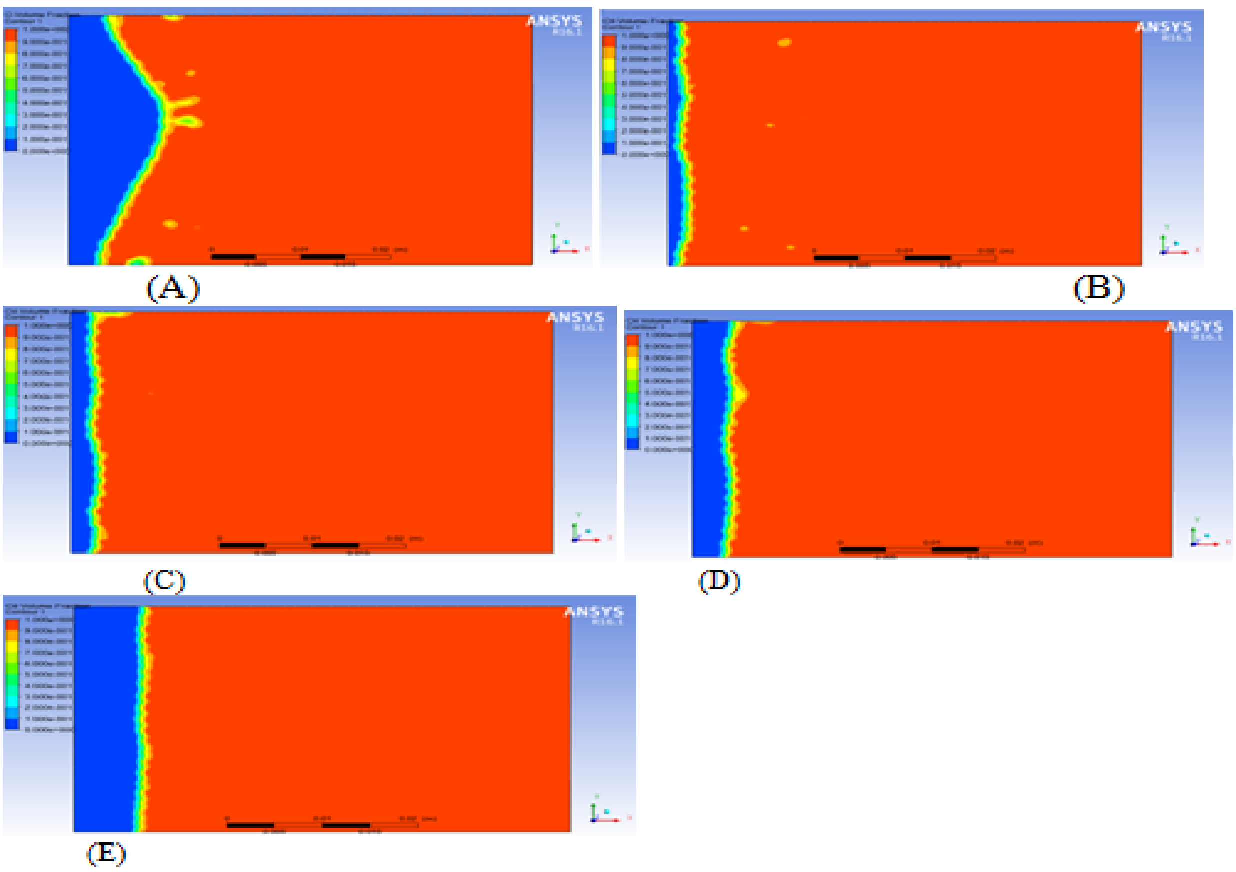


Figure 7:- visualization of volume fraction contour for brine water without and with PAM concentrations increases with crude oil, A)brine water, B)1000PAM, C)1500PAM, D)2000 and E)2500 PAM

Simulation oil release from porous media was depend on viscosity of injected fluid. This agreement with [33].Viscosity of aqueous solution was depended to make simulation for core sample as porous media. Oil is 3.115 cp more viscous than brine water with 0.5 cp viscosity which result high mobility ratio, easily movement in porous media, no slug solution and high permeability when pushing oil forward. Figure7 (A), shows clear viscous finger with unstable contact region between injected fluid and local oil. This result with [34], represent clear interface region between two fluids with amount of sharp fingers that result from low liquid viscosity. Parabolic velocity profile of brine water accelerate reach to break through point result less oil extracted, low sweep efficiency and remain high amount of oil in porous media.

Increase concentrations of PAM(1000, 1500, 2000 and 2500) ppm mixed with injected brine water in porous media. Viscosity of aqueous solutions be (4.51, 6.21, 9.11 and 13.39) cp from lower to upper concentration larger than oil viscosity. Therefore, decrease mobility ratio, movement in porous media reduced to release high oil amounts, increase slug for solution and low permeability when pushing oil forward. Figure7 (B, C, D and E), show reduced viscous finger with stable contact region between injected fluid and local oil with increase concentration. This result similar to [35, 36], show fewer viscous finger when viscosity of the introduced fluid was higher than viscosity of oil with stable displacement oil. Decreasing n values as show in table1, result high plug of velocity profile regionwith increasing concentration of PAM that increase oil recovery [37, 38].

CONCLUSION

Experimental study for PAM aqueous solutions as non-Newtonian fluid was performed by Cone - plate viscometer with (25-250) s^{-1} at 25C°.Physical, petro physical properties and core flooding test were examed. Also, numerical simulations to visualize the contact zone between injected fluid and oil in porous media. From this work, it can be concluded as following:-

1-Shear viscosity decreases with shear rate increase, temperature and brine concentration for all polymer aqueous solutions.

2- Shear thinning effect and non-Newtonian flow behavior increase with the PAM concentration increasing.

3-Clear nonlinear relationship obtained between shear stress and shear rate with increasing of PAM concentration.

4- Power low index n decrease and viscosity consistency K with increased the PAM concentration increasing.

5- Density, surface tension and oil recovery were increased with PAM concentrations increasing.

6- Injected 2500 ppm PAM after break through point result, reduced water cut amount and increase oil recovery magnitude.

7-High stability and low viscous finger was appear in contact zone by increase PAM concentrations solution.

8- Good agreement between experimental and numerical study.

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