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REVIEW OF PHASE INTERFERENCE IN MULTIPHASE FLOW FOR ENHANCING OIL RECOVERY

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Abstract

Study of multiphase flow is important in many natural and engineering systems such as the atmosphere, food, process, pipelines, cooling, petrochemical, and petroleum industries etc. In the petroleum industry, multiphase flow occurs both in recovery as well as at production stages. Its significance further increases in the secondary and tertiary recovery stages. The reservoir properties (fractures, heterogeneity in permeability, depth, porosity, saturation etc.) and the fluid characteristics (viscosity, density, and water fingering) mainly affect the efficiency of the water flooding for enhancing oil recovery. Hence, a comprehensive understanding of different phases flowing through the rocks/reservoirs, is essential for oil recovery from the unexploited and unconventional reservoirs, which are enormous in quantity. In the research documented here, comprehensive research review is carried out to analyse the use of different fluids when passing through different mediums. Gas (nitrogen and carbon dioxide) flooding is mostly used in the reservoirs with gas caps and in gravity drainage recovery processes, where it is needed to maintain the pressure of the reservoirs for efficient oil recovery, but inclination, permeability and depth of the reservoir adversely affect the efficiency of gas flooding. In the case of water if used for displacing oil from fractured media, researchers concluded that the fracture size, orientation, flow rates and fluid properties are responsible for displacing oil from the fractures. It is reported that oil recovery by water flooding is not as efficient as it is obtained by using surfactant, polymer and especially nanofluids. Studies show that surfactants reduce interfacial tension between oil and water, polymer increases viscosity of the displacing phase whereas the nanoparticles reduce interfacial tension as well as increase viscosity of displacing phase if proper

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quantity of the particles are mixed in the displacing phase. Experiments show that the recovery oil from fractured media, can be increased by more than 90% if nanofluids are used as a displacing phase.

Key Words: Multiphase flow; fracture; surfactant; polymer; flow regimes

1. Introduction

Petroleum is a naturally occurring hydrocarbon that accumulates in reservoirs with sufficient porosity and permeability ((Burchette, 2012; Craft et al., 2014; Boggs, Jr., 2006; Terry et al., 2014). Reservoirs chiefly contain one or more of oil, gas, and water typically in sandstone or limestone rocks (Terry and Rogers, 2014). Petroleum was first explored about four thousand years ago in Babylon and Greece (Chisholm, Hugh, ed., 1911; Fink, 2015) whereas the first oil well was drilled in China in 347AD (Fink, 2015). It was recognized earlier that on average, roughly two-third or more of the original oil in place remains in the reservoir after primary production (Boggs, Jr., 2006; SayedAkram and Mamora, 2011). The key challenge always faced by reservoir and production engineers is on how to raise the recovery factor (the fraction of the original oil in place that is produced); this is accomplished by enhanced oil recovery processes such as water flooding, chemical (e.g. surfactant, polymer etc) flooding or thermal recovery processes. The focus of the research documented here is on water flooding based methods.

Globally, fractured carbonate reservoirs are major sources of the oil. On a planetary basis, more than 60% of the remaining petroleum reserves are hosted in carbonate reservoirs which are mostly oil wet (Boggs, Jr., 2006; Agada, 2016). Depending on reservoir properties, secondary recovery processes such as water flooding have typically yielded an incremental 10 to 40% recovery factor but even after secondary recovery, a significant fraction of the oil remains in the reservoir. The main reasons for less-than-ideal recovery factor from these reservoirs is associated with complexity of multiphase flow through fractures, heterogeneity of the reservoir, the amount of storage of oil in the matrix, and the ability of oil to move from matrix to the fractures. To increase recovery from the reservoirs, a thorough investigation of the physics of the fluids is needed to analyse multiphase flow through fractures and interfaces developed during the flows.

2. Multiphase Flow

Single-phase flow is the flow of a fluid or combination of completely miscible solutions, which are chemically homogenous, isolated, and distinct from the other parts of the system. Multiphase flow is a simultaneous flow of two or more immiscible fluids separated by a boundary/interface (Bear and Bachmat, 1991). Multiphase flows in a system can also be defined as the flow of two or more materials with different states/phases and different chemical properties. Multiphase flows are important in many natural and engineering systems including the atmosphere, food industry, process industry, pipelines, cooling industry, petrochemical, and petroleum industry, to name a few.

In the petroleum industry, multiphase flow occurs more or less at every stage of the recovery and production processes. In reservoirs, oil exists mostly with gas, water, or both together within the formation rock that hosts the phases. The importance of multiphase flow increases in the oil recovery processes especially in secondary and tertiary recoveries. In secondary recovery processes, oil is produced by injecting water or gas to the reservoir. Waterflooding is considered the most effective and cheaper secondary recovery method, if feasible. Craft and Hawkins, (2014) described that waterflooding started more than 100 years ago. They suggested that reservoir characteristics (depth, heterogeneity, porosity, saturation, permeability etc.) and fluid characteristics (viscosity, density) affect the efficiency of water flooding. Fractures/faults in rocks, adverse reaction of water with the reservoir fluid, processing of the produced water to remove the hazardous material from the water, and viscous fingering are the major sources of problems associated with the waterflooding processes. Gas (nitrogen and carbon dioxide) flooding is often carried out in reservoirs with gas cap and in gravity drainage recovery process, where it is needed to maintain the pressure of the reservoir for efficient oil recovery. Inclination, permeability and depth of the reservoir mainly affect efficiency of the gas flooding (Craft and Hawkins, 2014).

In the tertiary/enhanced oil recovery methods, miscible, thermal and chemical flooding is carried out to recover the remaining oil from a reservoir. The oil, mostly trapped in small pores or regions of the fractures due to capillary forces, which is challenging to move from the system to the production well. In the tertiary recovery processes, the oil is displaced from the surfaces/pores, which flow out to the production well by developing a displacing flow with the help of increasing the viscous forces and decreasing the capillary forces between the displacing and displaced phases. The residual oil can also be mobilized by controlling the capillary number or mobility ratios, especially in the chemical injection processes by using chemical additives such as surfactant or polymer that change the in-situ properties of the phases and pores/fractures surfaces (Craft and Hawkins, 2014). Miscible flooding processes are carried out by injecting a fluid phase (typically carbon dioxide or nitrogen) to the reservoir, which on mixing with the residual oil, lowers capillary forces (via interfacial tension) between the phases and improves oil recovery. In thermal recovery processes, migration of the heavy oil is carried out by injecting hot water or steam to the reservoir, which reduces viscosity of the oil consequently raising its mobility.

Multiphase flow is studied by different researchers for various conditions/scenarios. Some of them studied multiphase flow through distinct passages, while a few researchers have studied flow of various fluids through rock samples or fractures. Detail of a few of these studies is presented here.

3. Multiphase Flow in Pipes

To understand multiphase flow in narrow gaps (fractures), it is instructive to examine multiphase flow in pipes.

Although there are many studies of two-phase flow in pipes in the literature, in which, most of them focus on flow patterns or instabilities created in air-water flow through vertical, inclined and horizontal circular pipes. The earliest published work on classifying flow patterns in pipes was done by Baker,(1957) who has observed eight flow regimes in the air water flow. Many published studies have classified flow patterns created by the flow of air or gas and water through circular pipes, for examples (Gibson, 1913; Govier, 1958; Hewitt et al., 1970; Govier et al., 1972; Mandhane, 1974; Crawford et al., 1984; Troniewski et al., 1984; McQuillan et al., 1985; Brill et al., 1991; Ansari et al., 1994; Hasan et al., 1998; Furakawa et al., 2001; and Rozenblit et al., 2006). There are fewer studies on liquid-liquid flows in pipes. Russel et al., (1959) observed bubble, stratified, and mixed flow patterns in multiphase flow of oil (18 cP) and water in horizontal circular pipes. Charles et al. (1961) studied flow regimes created in the flow of water with three different viscosities (6.29 cP, 16.8 cP, and 65 cP) and same density 998 kg/m3 oil at different flow rates of the phases in a pipe of 26.4 mm diameter and 7.3 m long test section (Figure 1). They noticed that the flow patterns of the phases depend on their superficial velocities. They observed same flow patterns for all the oils except at low water flow rates. They classified the flow patterns into water drops in oil, oil in water concentric, oil slugs in water, oil bubbles in water and oil drops in the water (Figure 2)

Hewitt et al., (1970) and McQuillan et al., (1985) classified flow patterns created in a gas-liquid vertical upward flow as bubble, slug, churn and annular flows, displayed in Figure 3, which depend on the flow rates of the phases, pipe geometry, and flow conditions. In the figure, the gas flow rate is increased from left to right. Each flow pattern has different differential pressures, which depicts the importance of the flow patterns with increase in flow rates.

Brauner et al., (1992) concluded that the pipe diameter and fluid properties affect the nature of the flow regimes. Johnson, (1998) witnessed air-water flow patterns in a 1-inch diameter horizontal pipe and classified them into stratified, slug, annular mist and elongated bubble obtained at increasing velocities of air. Angeli et al., (1999) investigated flow patterns in oil (viscosity 1.6 cP and density 801 kg/m3) and water flowing through horizontal 1-inch pipes made of different materials. They injected mixture of the phases with velocities ranging from 0.2 to 3.9 m/s. They observed that the flow patterns change with increase in velocity of the phases and were classified into four groups as illustrated in Figure 4. The first one is stratified wavy, where the phases are segregated due to the density difference between the phases with a disturbed interface between the two phases. The second one is stratified wavy with drops appeared near the interface. The third type is the three layers' flow pattern' where the water and oil flow at the top and bottom of the pipe while the droplets are at the interface. The fourth one is referred to as stratified mixed where the faster phase is continuous and the other phase flows as drops with both phases dispersed in each other.

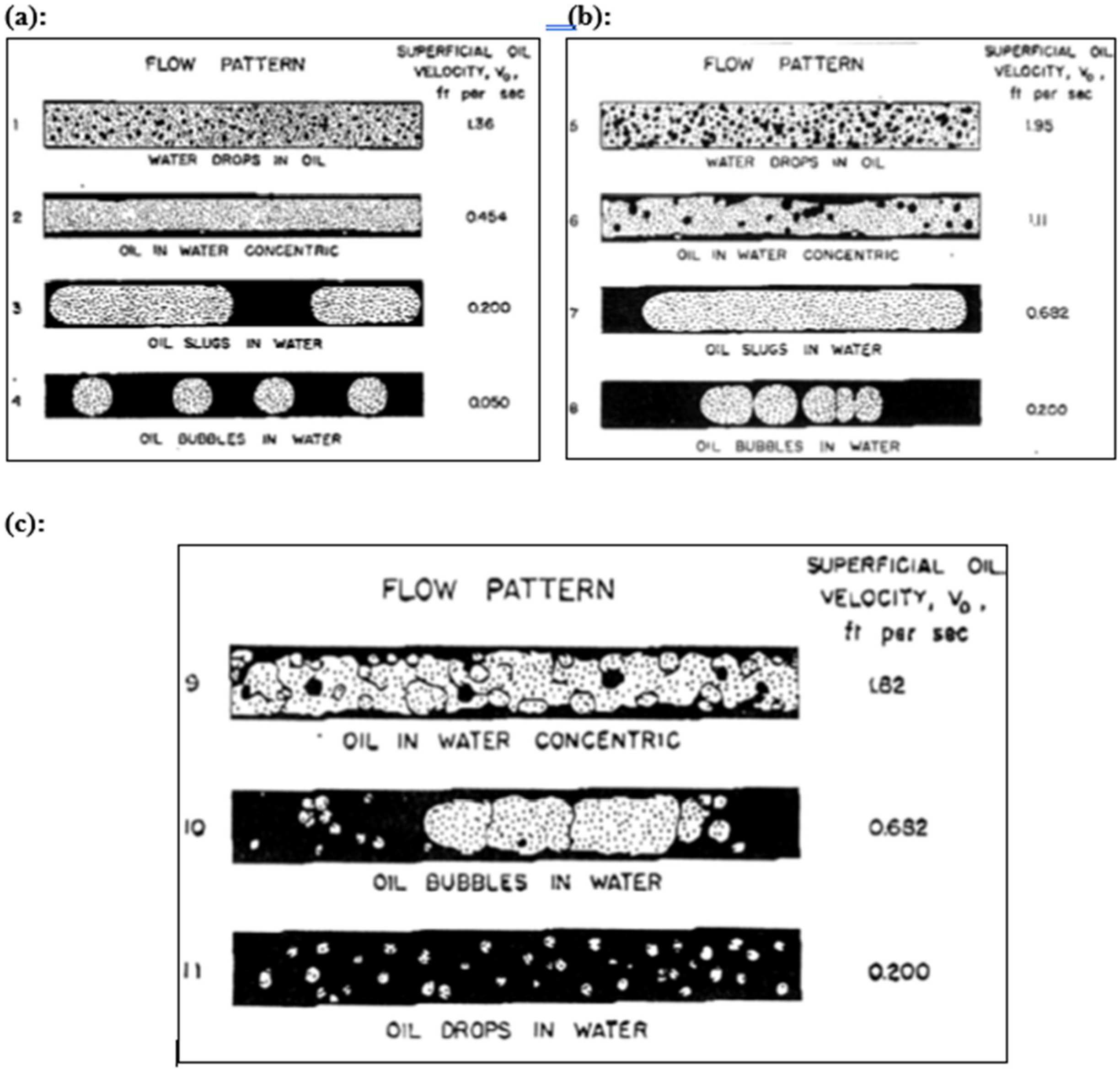


Figure 1: Flow patterns observed by Charles et al. (1961) in the oil-water through a pipe. (a): Flow patterns created in the flow of water flowing at constant velocity (0.3m/s) with 16.8 cP oil flowing at different velocities, (b): water flowing at 0.21 m/s with 16.8 cP oil flowing at different velocities, (c): water velocity 0.62 m/s and 16.8 cP oil flowing at different velocities

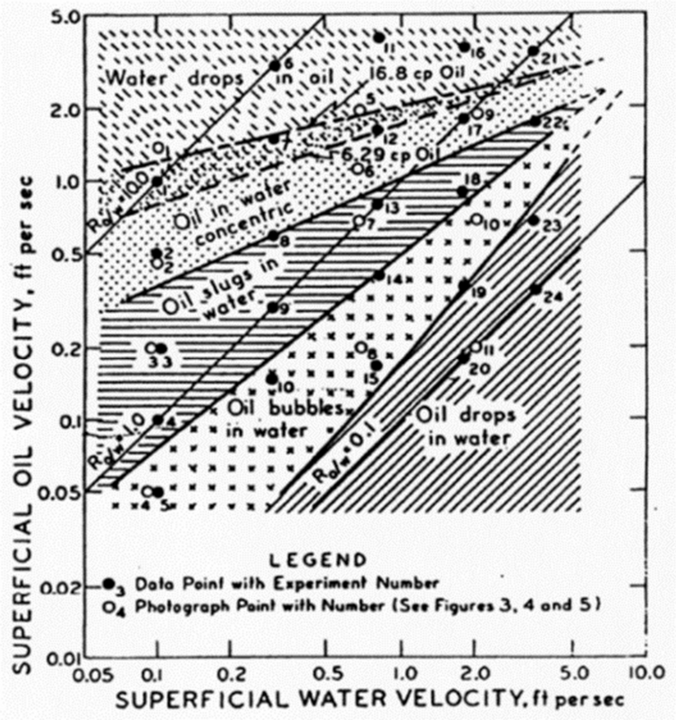


Figure 2: Flow patterns classified by Charles et al., (1961) in the flow of water with 6.26 cP and 16.8 cP oils at different superficial velocities in a pipe

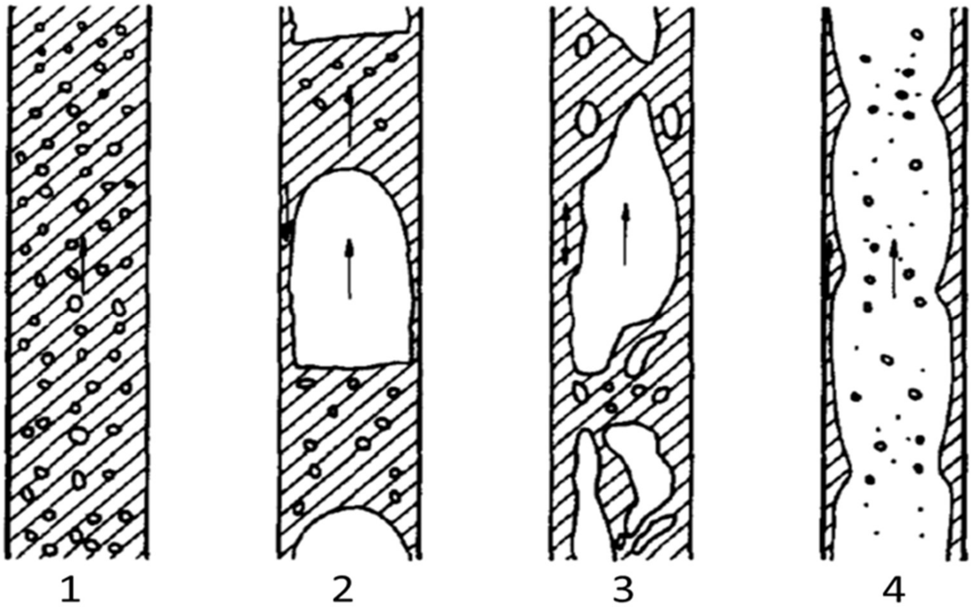


Figure 2.3: Flow patterns observed by McQuillan et al., (1985) in gas/liquid upward flow through a vertical pipe. 1. Bubble, 2. Slug, 3. Churn and 4. Annular

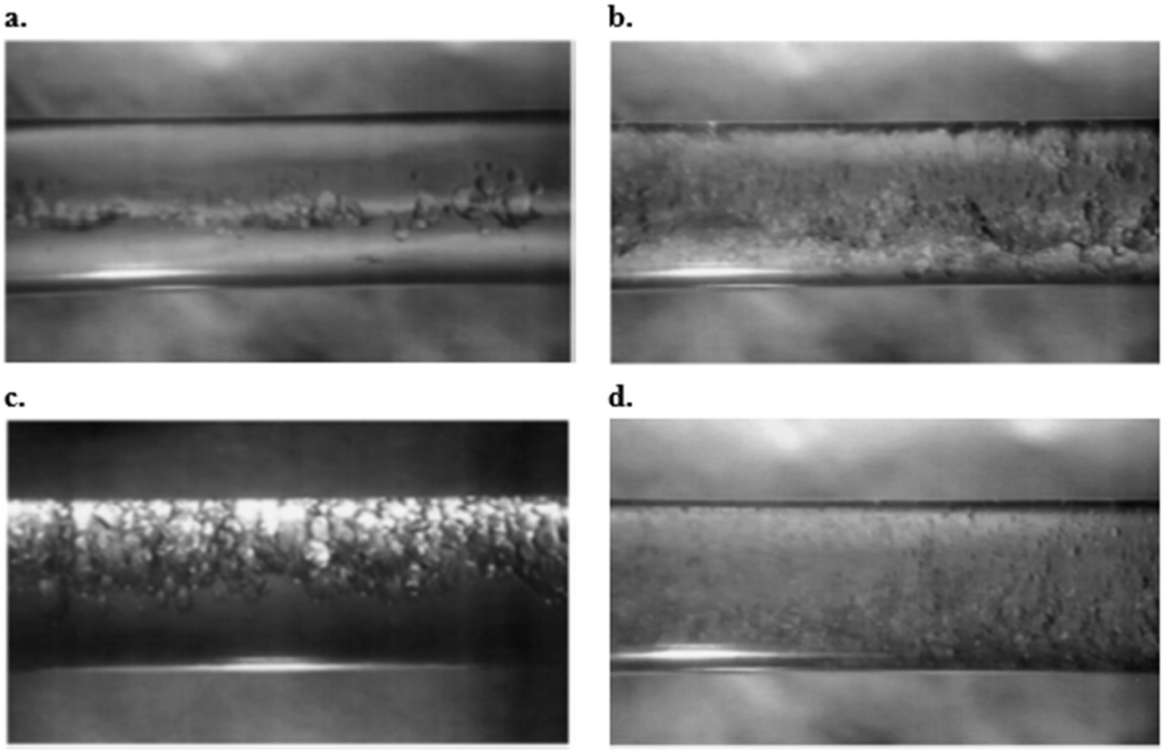


Figure 4: Flow patterns observed by Angeli et al., (1999) in an oil-water flow mixture at different velocities through pipe. (a) stratified wavy with drops flow pattern, (b) three layers flow patterns, (c) stratified mixed with water layer flow pattern, and (d) mixed flow pattern (Angeli et al., 1999)

4. Multiphase Flow in Narrow Gaps

Like multiphase flows in pipe, multiphase flow in planar gaps exhibits multiple flow regimes each of which occur at different flow rates of the phases and at different pressure gradients. A number of literature focussed on multiphase flow in fractures, most being on air/gas and water systems (Fourar et al., 1993; Fourar et al., 1995; Persoff et al., 1995; Kneafsy et al., 1998) and many more, while Katsuhiko, (1976); Reis, (1990); Jensen, (1992); Rossen et al., (1994); Dindoruk, (1995); Sumnu et al., (1995); Nicholl et al., (2001); Ayatollahi, (2005); Shad et al., (2008), Shad et al., (2010), Al-Turki et al., (2012), and Al-Turki et al., (2013) studied liquid-liquid flow through fractures. Most of them focussed on the study of flow regimes created in the two-phase flow, which play a vital role for an efficient oil recovery.

Apart from flow structures, multiphase flow through narrow gaps were quantified through relative permeability curves and interference analysis of the phases (Scheidegger, 1974; Shad et al., 2010; Al-Turki et al., 2012). Relative permeability of a phase can be calculated by using Darcy's law. There are also some other models developed for calculating relative permeabilities for example X-Curve Model (Romm, 1966); Corey Model (Corey, 1954); Brokes-Corey Model (Brooks and Corey, 1964); Viscous Coupling Model (Fourar and Lenormand, 1998); Aguilera Model, (Aguilera, 1995); Homogeneous Single Phase Model (Delhaye, 1981); Lockhart and Martinelli's Model (Lockhart and Martinelli, 1949), and Shad and Gates Model, (Shad et al., 2010). Most of them depend upon the saturation of the phases (volumetric fraction of phase in the total fluid volume) and pressure gradient.

4.1. Gas-Liquid Flow in Narrow Gaps

In case of two-phase air/gas-water flow in narrow gaps, several studies in the published literature evaluated flow regimes including Troniewski et al., (1984); Ali et al., (1991); Mishima et al., (1992); Wilmarth et al., (1993); (Fourar et al., 1993; Fourar et al., 1995; Polonsky et al., (1998); Indraratna et al., (2003)) and many more. Majority of them focussed on the study of flow structures created in the flow of the phases and the overall behaviour of the multiphase flow. For example, Fourar and Bories, (1993) experimentally investigated air-water flow through horizontal smooth and roughened walled fractures and concluded that the flow structures change from bubble to chaotic patterns with an increase in the flow rates. They explored the homogeneous single phase model (HSPM) where the two phases are represented as a single homogeneous equivalent phase and found that this model yields a good fit to relative permeabilities as derived from the experimental data. In 1995, they repeated their experiments and got the same results as of 1993. Indraratna et al., (2003) conducted experiments on the air-water flow through rough walled fractures and observed phase interference as the sum of relative permeabilities is less than 1. Similarly, the research on air/gas-water flow through narrow gaps or fractures was performed by Diomampo, (2001); Chen et.al., (2005); Chen et al., (2007); and Chima et al., (2012) (Fourar et al., 1993; Fourar et al., 1995 and Indraratna et al., (2003) which is summarized in Table 1.

4.2. Liquid-Liquid Flow in Narrow Gaps

Flow in thin fractures is different from the flow in the big sized rectangular ducts, as in the thin gaps, capillary forces often dominate over viscous forces, gravity, and pressure (Sadatomi, 1982). Liquid-liquid flow in gaps depends upon the viscosities, densities, interfacial tensions between the phases, flow rates of the phases, and geometry of the fracture. To understand the behaviour of two-phase flow, it is important to analyse the structures created in the flow, which are mostly affected by viscosity, density (in vertical flow), flow rates, and other properties of the phases. In reference to the difference of the viscosities Hill, (1952); Chouke et al., (1959); Saffman-Taylor, (1958); Pan et al., (1996); Fernandez et al., (2005); Al-Turki, (2012), and many others studied liquid-liquid flow in thin gaps.

4.2.1. Oil - Water Flow Through a Thin Gap or Fractured Media

Majority of the studies on multiphase flow in narrow gaps have focused on gas-liquid flow. There are limited number of studies on liquid-liquid, and in particular, oil-water flow in narrow gaps (Romm, 1966; Pieters et al., 1994; Pan et al., 1996; Shad et al., 2008; Shad, 2009, Khosravi, (2012), and Al-Turki, 2013) are a few of them. A summary of key studies is provided in Table 2.

Table 1. Summary of air/gas and water flow through fracture or fractured porous media

Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
Fourar and Bories, (1993)	To study 2 Phase flow through a fracture	Air-water	• Horizontal gaps of contacted surfaces, 1mm and 1.1mm, (1fracture of smooth & 3 of rough surfaces each has 0.5 x 1 m area)	• At low q_{gs}, bubbles flow patterns and P_c is high while at higher q_{gs}, chaotic flow pattern, with no change in dp observed.
Fourar and Bories, (1995)	To analyse flow structures in different gaps	Air-water	• Gaps used: 1mm made of glass plates & fractures of different gaps from 2 bricks.	• Six types of flow patterns at different air flow rate. • Analytical equation developed for pressure gradient had a good agreement with Lochart-Martinelli model.
Indraratna et al., (2003)	To study 2 phase flow in rough fractures	Air-water	• Experimental and numerical modeling • Use of extended Darcy's law and k_{rs} concept	• Cubic law is not valid at high ∇P_s in tight and rough fractures and $\sum K_{rs} < 1$ at same pressures of water & oil • Hydraulic diameter and tortuosity decrease with roughness.
Diomompo (2001)	To verify that k_r curves follow X-curve or Corey model.	Nitrogen/gas-water	• Smooth and rough fractures of area 12" × 14" • The gas water ratios ranged from 10^{-1} to 10^4. • Added a fraction factor to Darcy's equation.	• Instability of pressure, no specific flow patterns. • At $P_s < 0.5$ psi, k_{abs} changed due to pushing the plates away by the fluids but at $P_s >$ 0.5 psi k_{abs} const. • No match of results of smooth and rough fracture
Chen, (2005)	To model effects of phase changes and roughness on k_{rs}	Air-water, & steam-water	• Single fracture in Hele-Shaw Cell	• Strong interactions b/w fluids and fracture roughness • Steam-water's k_r, flow structures, and residual phase saturations is different than air water flow

Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
Chen and Horne, (2005)	To study effects of roughness on k_{rs} and to develop a tortuous model	Nitrogen-deionized water	- Water wet fracture - smooth, homogenously rough (HR) and randomly rough (RR). - Increasing flow of gas and decreasing of water - Used ime averaged data of pressure, flow rates and saturations for calculating kr_{avg}	- At high gas flow rates, more regular tortuous paths formed in HR fractures as compared to RR fractures. - The k_{rws} are irregular at high water saturations - Tortuous Channel Model (TCM) yielded good results - The flow structures depend upon saturations
Chen et al., (2007)	To analyse flow structures effects on k_{rs} & develop a model	Air water	- Air wetted single fracture - Validation of X-curve model, use of Stokes equation, Darcy's & locally applied Cubic laws.	- In no Δp, k_{rs}=saturations, 5 structures observed depended on the viscous forces and flow rate of the gas, and new model considers deviation from X-curves
Chima and Geiger, (2012)	To develop a model and validate Romm's equation	Gas-water	- Numerical model for k_{rs} developed for flow in parallel smooth walled fracture (1×0.5×0.001m) fracture in glass plates.	- Non-linear k_r curves obtained by the model, function of saturation and viscosities, yielded good match with experimental results than Romms's model

In addition to flow regimes, many studies have examined relative permeabilities as a mean to understand the nature of multiphase flow in narrow gaps. This follows the application of relative permeabilities to study multiphase flow in porous media. For example, Meloney et al., (1997) analysed oil-water flow through vertical smooth walled fractures with 787 and 51 micron gaps. They determined that density and flow directions of the fluids are key parameters that affect relative permeability behaviour. They concluded that in large gaps, the relative permeabilities of the phases are not depended on their saturations but in narrow gaps, saturation plays a vital role in setting of the relative permeability of a phase. Kulatilake et al., (2001) applied different normal stresses on a single fracture in core and investigated flow of fluids, effective area distribution, and fracture closure at each stress condition. They passed water through fracture at different flow rates and measured the fracture closure by using a profilometer. They observed that orientation of a fracture and nature of the fractures network affects the flow of fluids moving through it. They claimed that in rough walled fractures, the cubic law (based on planar Poiseuille's equation) is invalid since the phase channels are tortuous and the effective stresses are not uniformly distributed within. In addition, Putra et al., (2004) numerically simulated and experimentally observed oil-water flow through a single fracture within rock cores at different confining pressures. They applied 500, 1000 and 1500 psig confining pressures on fracture apertures with gaps of 56.4, 40, and 20 µm, respectively. In the case of simulation, they changed the pressures with flow rate of water equal to 5 cc/hr. They found that the relative permeability, calculated by Darcy's equation with the assumption of smooth fracture surfaces, are not correct because of tortuous flow induced from the surface roughness. Also, due to the surface roughness, simulations of the flow rates and differential pressures at same conditions are not identical. On the basis of this analysis, they added a friction factor to the calculation, which is a ratio of the absolute roughness to the hydraulic diameter. The equation developed considered roughness of the surface and the deviation of permeability from the cubic law. They concluded that there is a linear relationship between the fluid flow rates and fracture apertures. After incorporating the friction factor for relative permeabilities in the simulation, their experimental results were consistent to the simulation. Therefore, they recommended that for rough surfaces, accurate modeling is possible provided the roughness is included in the model.

4.2.2. Oil - Surfactant Solution Flow Through a Thin Gap or Fractured Media

The volumetric sweep efficiency and recovery of oil from an oil wet fractured medium is low in water flooding due to the absence of capillary imbibition and viscous displacement of trapped oil in the matrix (Babadagli, 2002). Advanced techniques should be applied to recover trapped oil from the fractured reservoirs. One of them is the use of surfactants which acts at interfaces of oil and water by diverting its non-polar part to the oil phase and polar end towards the water phase. As a result, the interfacial tension between the phases drops i.e., the energy required to deform the interface, falls. It displaces oil from tight pores or converts continuous oil phase to droplets host in the water phase results in raising effective mobility and overall recovery of the oil.

Table 2. Summary of oil-water flow through fracture or fractured porous media

Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
Romm, (1966)	To analyse fluids flow by k_{rw} and k_{ro}	Kerosene oil-water	• Smooth walled fracture	• K_r of a liquid is equal to its saturation • Sum of k_{rs} is equal to unity

Reference	**Objectives**	**Fluids Used**	**Experimental Set up and Method**	**Findings**
Pieters & Graves, (1994)	To validate E. S. Romm's claim	Kerosene and water	• Kerosene oil saturated fracture (0.00254cm), Hele-Shaw Cell is used. • k_{rs} were calculated by Weldge's equation.	• k_{rs} of fluids are not linear with saturations. • K_{rs} are effected by different factors as the fracture behaves like a porous media.
Pan et al., (1996)	To find phase interference and their k_{rs} of phases	Oil and water	• Smooth walled horizontal fractures were used • Model-I: Injected fluids separately • Model-II: Injected mixture of fluids	• Phase interference is a function of capillary forces (F_c) • K_{rs} in Model-II < Model-I and their sum in both is < 1 • Water fingering and chaotic flow in Model-I at high q_o
Shad et al., (2008)	To develop analytical model for k_r and study flow structures	Heavy oil and water	• Drainage and imbibition processes through vertical and horizontal, oil wetted smooth walled fracture	• Droplets creation & k_r variability is high at low q_s & Δp_s • Water fingering increased with increase in q_w • Their model fits well with experimental data but overestimated k_{ro} and underestimated k_{rw}
Shad et al., (2008)	Studied motion/structures of liquid in a vertical thin gap	Heavy Oil and Water	• Vertical Hele-Shaw Cell & horizontal flow with gap=0.0226cm • Numerical model developed for k_{rs} considered Nc, μ_s ratio, gap & droplet sizes	• Small droplets, elongated droplets, churn and channel flow patterns observed. • Experimental results fitted well with the numerical models results.

Reference	**Objectives**	**Fluids Used**	**Experimental Set up and Method**	**Findings**
Shad et al., (2010)	To analyse the fluid patterns and its effects on transition limits	Heavy oil and water	• Horizontal and vertical Hele Shaw cells • Drainage	• Flow patterns change with flow direction, flow rates, k_r and geometry of the fracture, affected mass, momentum and energy exchange and ΔP • Velocity, shape and stability of discontinuous phase depend upon the μ_s, $\Delta\rho_s$, P_c and gap
Khosravi, (2012)	To find k_{rs} in a fracture with different flow rates and displacement mechanisms	Oil-water	• Discussed Darcy's law, modified Darcy's equation, Corey Model for steam-water, Brooks-Corey Model for steam-water in porous media at capillary pressure and X-curves for K_r in fractures.	• Gravitational forces are not important on lab scale but it does on field scale. • Recommended steady state method for finding K_{rs}. • Suggested methods for transferring lab data to the reservoir and different flow directions give different S_{wis} and different production curves

Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
Al-Turki, (2012)	To studies frontal displacement in a single fracture at different inclinations and opposite directions flows	Light oil and Water	• Drainage and Imbibition in Hele-Shaw Cell (single smooth/rough oil wetted fracture) at 0, 30, 60 90 degrees inclination). • Model-I: gap = 0.0127 cm • Model-II: gap = 0.0254 cm • Model-III: gap = 0.0381 cm • Used Darcy's for K_{rs} at N_{crs} <10	**Smooth Walled Fracture:** • Viscous forces dominate P_c in high water flow Rates/larger gaps/low saturations. • Aperture size affected K_{rw} slightly but not k_{ro} • Observed droplet and channels in all models • k_r increased with gap, inclination and down dip flow. In imbibition k_{rs} in horizontal > up-dip and down-dip flows **Rough Walled Fracture:** • Roughness increased viscous forces, phase interference & k_{rs} • K_r increased with inclination and down-dip flow • $\sum k_{rs} > 1$ in down-dip vertical fracture due to gravity • In imbibition, k_r curves moved to higher S_w in up-dip inclined flow than horizontal flow

Porter, (1991) discussed the dispersion of oil into droplets in the presence of a surfactant and explained that surfactants occupy the interface of oil and water and facilitates dispersion of oil into water phase in the form of droplets.

The first field test of micellar solutions for improving oil recovery was carried out in Easter Illinois oilfields, USA in 1962 (Geogarty et al., 1972). There was no pre-water flooding and therefore, surfactant flooding was not effective. However, in another attempts with a pre-water flooded reservoir, they achieved reasonably good results. Surfactant flooding for oil recovery was analysed by a number of researchers and majority of them concluded that the surfactant solution reduces interfacial tension between the displacing and displaced fluids and converts the rock surface from being less hydrophilic to more hydrophilic (Rosen et al., 2012; Ferno 2012).

Park et al., (1994) experimentally examined the effect of a surfactant on air bubble and water droplets of 1.3 to 2.1 cm plan-form diameter with and without surfactant driven in silicon oil (viscosity 97 cP) through a gap of 17.8 × 86.4 × 0.9 × 1.8 cm dimensions (Hele-Shaw cell). They concluded that the surfactant effect on the air bubble's shape and movement is not significant but t he effects of organic surfactant (sodium dodecyl sulfate, SDS) on the water droplet's shape are substantial which in turn reduce the translational velocity of water droplets. Wilkens et al., (2006) proposed that interfacial tension should be considered for predicting flow patterns in multiphase flow through porous media and concluded that interfacial tension is reduced after adding surfactant (SDS) to air-water flow through a horizontal system. Liombas et al., (2006) studied the interfaces in two-phase flow through inclined pipe and concluded that surfactant delays the formation of wavy flow regime and reduces the pressure drop. Kianinejad et al., (2013) experimentally showed that SDS yielded 79%, Linear Alkyl Banzene Sulfonate (LABS) 66% and water 32% oil recovery from a horizontally laying model etched with inclined fractures. The oil recovery is increased by SDS from a matrix by increasing the breakthrough time of the solution. They observed that the fractures oriented perpendicular to the pressure drop yields greater recovery than the fractures oriented in the direction of the pressure drop. In other studies, Chen et al., (2001), and Hirasaki and Zhang, (2004) used surfactants for oil recovery from fractured media and concluded that the surfactants enhance oil recovery from the rock. Simulations carried out by Abadli, (2012) also showed that the oil recovery improves with the addition of surfactant in the water flooding.

Oil-surfactant solution systems have been extensively studied by Standnes et al., (2000); Chen et al., (2001); Babadagli, (2001); Seethepalli et al., (2004); Adibhatla et al., (2008); SayedAkram et al., (2011); Samanta et al., (2011); Hirasaki et al., (2011)); EIMofty, (2012); Leonce, (2012); Ferno et al., (2012); Kianinejad et al., (2013); Park et al., (1994); Hashimoto et al., (2008); Razmi et al., (2012), and so on. A summary of some research carried out in surfactant-oil flow examination, is listed in Table 2.3. In general, most studies are consistent and show that the addition of surfactants raise oil recovery from the host medium.

Table 2.3. Summary of oil-surfactants flow through fracture or fractured porous media

Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
Park et al., (1994)	To evaluate effects of surfactant on air bubble & water droplets	Air, water, oil and surfactant	• Hele Shaw cell (17.8 cm x 86.4 cm) of 0.9 mm and 1.8 mm gaps	• Surfactants do not affect the shape & movement of the air bubble but it reduces translational movement and changes shapes of the water droplet.
Babadagli, (2001)	To study of recovery from cores by water,	Light/heavy oil, surfactant & polymer	• Flooded water, surfactant & polymer through cores saturated	• Got a greater and faster oil recovery with surfactant than water and polymer.

Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
	surfactant & polymer		with light and heavy oil - Analysed recovery of oil for all fluids	
Feranndez et al., (2005)	To examine instability in Hele-Shaw cell dipped in/out of surfactant solutions	Different Concentrations of SDS Surfactant	- (64×15×0.031cm) fracture in Hele Shaw cell - The cell is dipped in and withdrew of a surfactant solution. - Instabilities developed at pulling/dipping	- Fingering depends upon the cell velocity and concentration of the SDS surfactant - Observed drifting fingers, merging of fingers, air bubbles ejection and steady patterns
Seethepalli et al., (2004)	To experimentally study the interaction of surfactants with a core of carbonate reservoir	Oil and surfactant solutions	- Flooded oil saturated core with different surfactants - Examined the effects of wettability, recovery and fluid properties	- Anionic surfactants (SDS etc) - changed wettability to intermediate water wet, - reduced interfacial tension - enhanced oil recovery > 50% of the OOIP.
Adibhatla et al., (2008)	To find effects of surfactant on IFT, contact angle, k_{rs} & oil recovery	Oil and surfactant solution	- Wetted fractured carbonate reservoir rock core with oil - Flooded it with 0.05 wt% anionic surfactant.	- IFT & contact angle reduced, gravity drainage, K_r & oil recovery (50% of OOIP) increased - Change in the surfactant concentration effected IFT and wettability but not oil recovery
Hashimoto et al., (2008)	To observe dynamic instabilities and flow patterns of a water droplet	Oil, Tween20 and Span 80 surfactants	- Hexadecane saturated fracture in Hele Shaw cell (2-5 mm wide) are flooded by the surfactants in	- The droplet expanded side wise & broke into small droplets due to shear driven instability at low IFT

Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
	in hexadecane.		different experiments	• At low SDS, the water droplets united • Instabilities depended on the flow.
Samanta et al., (2011)	To examine oil recovery by flooding SDS and polymer.	99% SDS, PHPA Polymer	• Flood SDS (99%) surfactant and PHPA polymer through an oil saturated sand pack.	• 0.5PV-SDS increased oil recovery by 20% OOIP • PHPA after SDS flooding increased oil recovery by 2.78% OOIP more than surfactant.
SayedAkram & Mamora, (2011)	To simulate effects of natural fracture on polymer-surfactant efficiency in a carbonate light oil reservoir.	Oil, polymer and surfactant	• Used DPDP model and CMG Stars for simulating chemical EOR processes from a 1/8 of a 20-acre 5-spot pattern • Water is injected before and after chemicals. Fracture is represented by zero P_c and straight line k_r and considered adsorption in the rock	• The chemicals increased viscosity and mobility of oil. • DPDO has drawbacks in fracture spacing, Surfactant increased water wettability, gravity effect and oil recovery, and reduced IFT. • S_w increases with increase in water injection. • Surfactant effected outlet & fractured core more length, orientation and matrix flow in heterogeneous system. • Water-Surfactant polymer (WSP) flooding has 15 % more recovery than a base case model. • Polymer oil recovery is faster and more than surfactant • Surfactants in water lowered oil recovery at high S_{ws}

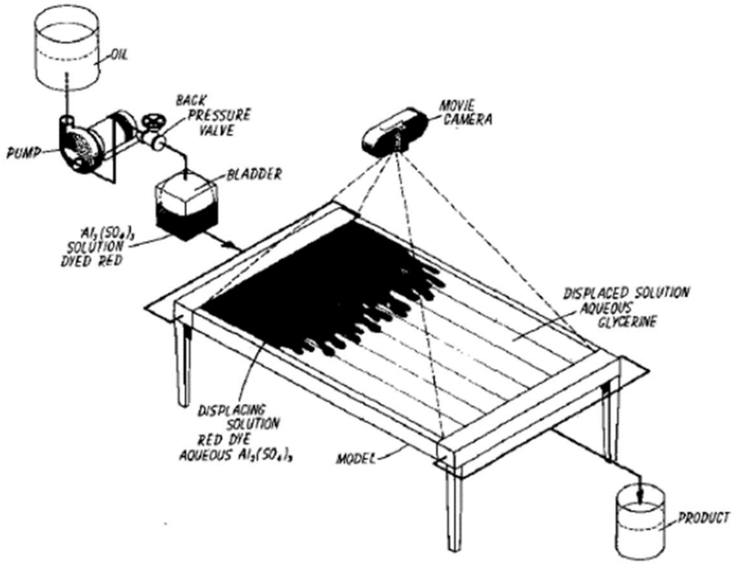
Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
Razmi et al., (2012)	To investigate oil recovery from fractures	Heavy Oil, SDS, LABS and water	• Flooded different angled micromodels fractures in glass plates by SDS & LABS	• SDS yielded more recovery than LABS and water • Oil recovery increased with number of fractures and in orthogonal fractures than parallel
Ferno et al., (2012)	Observed surfactant flooding via oil wet fractured carbonate core after 2 water floods	Surfactant solution and oil	• 1mm gap in core is placed between two cores and is flooded for 24 hours with surfactant at 2cc/hour. • Average saturations is found from material balance by MRI signals.	• than inlet and reduced ΔP requirement for water flooding.
Kianinejad et al., (2013)	Examine surfactant efficiency in fractures	Surfactant & oil	• 5 spot system in an oil wet fracture of different sizes and is flooded with SDS surfactant	• Surfactant increased breakthrough time & oil recovery. • Longer perpendicular to the ΔP fractures yield more oil

4.2.3. Oil and Polymer Flow in Fractures/Fractured Media

The use of aqueous polymer solutions for improving oil recovery due to mobility control and viscous fingering reduction has been widely reported. Carney et al., (1973) explained that different polymers behave differently but typically it is expected that polymer enhances viscosity of the injected fluids consequently lowers its mobility and its flow rate through the media. As a result, the effective permeabilities of both the aqueous (mainly) and oil (to a lesser extent) phases declines due to adsorption of polymer on the pore throats. They reported that polymer reduces brine permeability by 77%, whereas the oil permeability is reduced only by 6%. The results suggested that polymers reduce the water-oil ratio (WOR) and increase oil recovery.

Benham and Olson, (1963) conducted polymer-flooding experiments in two Hele-Shaw cells, one unpacked and other packed with glass beds. Their experimental set up and fingering observations obtained are shown in Figure 5. They measured saturation and velocity of fingers from images taken during their experiments by tracing them on large sheets. They noticed that the fingers do not originate from one point but evolve from different points in different directions. Frontal distortion rate increases linearly with position (up to 22.5 inches) and beyond this length, it starts to decrease due to diffusion that becomes prominent after about 24 inches of front movement. In the case of mobility ratio effects on fingering, they reported that finger growth increases with enlargement of the mobility ratio but their growth in the packed model is less than that of the unpacked Hele-Shaw model. The finger's growth rate has linear relation with the finger velocity but in the packed model, the finger velocity has less effect on its growth. In addition, the growth rate of the finger is not affected by the initial shape and frequency of the fingers. From decay of the fingers with distance, Benham and Olson expected that fingers would diminish in long cells. This has not been proven in the field scale reservoir operations where water breakthrough occurs.

Mungan, (1971) studied the role of rheological properties, polymer concentration, and surface action of polymer on oil recovery in polymer solution flooding. As depicted in Figure 2.6, addition of polymer to the injected solution reduces the mobility contrast and consequently a stable displacement is resulted. Similarly, Lakatos et al., (1981), and Broseta et al., (1995) investigated polymer retention on the rock surface and its effects on the fluid flow. Daripa and Pasa, (2005) analytically and Donaldson, (1985); Wassmuth et al., (2009); SayedAkram and Mamora, (2011); Clemens et al., (2012), and Ying-jie et al. (2013) experimentally observed that polymer solution increases oil recovery from reservoirs. A summary of their work along other research is listed in Table 2.4.



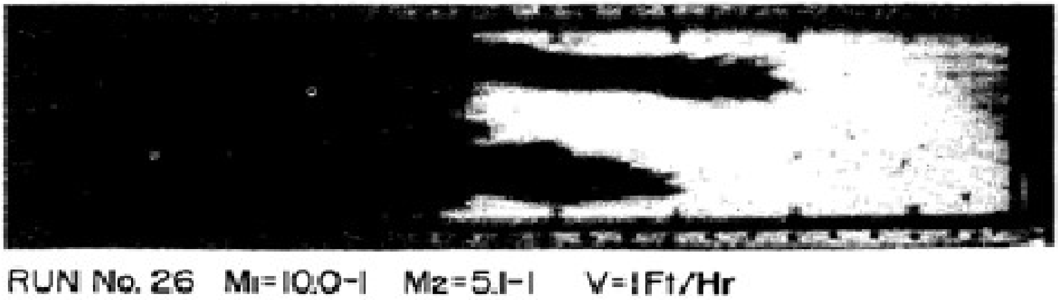
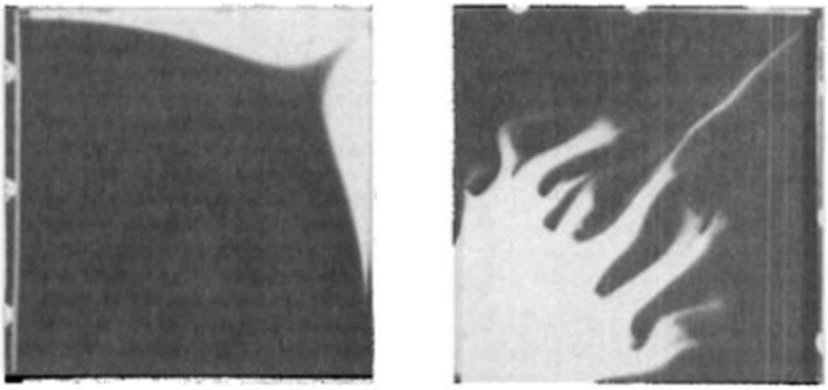


Figure 5. Experimental set up and fingering observed by Benham and Olson, (1963)



Favorable viscosity ratio, 3 (stable)

Un-favorable viscosity ratio, 30 (uns]table)

Figure 2.6: Interfaces and fingerings at two viscosity ratios observed by Mungan (1971): injection of polymer solution into the glycerin-wetted Hele-Shaw cell stabilizes the front

Table 2.4. Summary of oil-polymer flow through fracture or fractured porous media

Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
Benham et al., (1963)	To study fingering and effects of various parameters and properties on the fingers	Less viscous mineral oil, polymer & glycerin	• A gap (1×4×0.0052ft)-Hele-Shaw cell. • Two models are prepared, one with smooth walled & other roughened walled. • Different mobility ratios	• Observed long fingers and less oil recovery in the first model, while short fingers and more recovery in 2nd. • Fingers growth rate and velocity is greater in open Hele-Shaw cell than packed cell. • No effect of finger's shape on its growth

Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
Mungan, (1971)	To examine rheological properties of polymers	Polymer solution, light oil and glycerin	• Different concentrations of polymer adsorbed on silica sand pack samples of 20×2 in (dia) • Finger analysis in (26.8×26.8×0.006cm) gap in Hele-Shaw cell and a porous media of 12 x 12 x1 inch sandstone blocks were used	• Polyelectrolytes increased viscosity more than others • Viscous fingering behaviour has linear relation with its concentration due to x-linking of molecules. • Oil recovery increased by 84% & 28%for viscosity ratios of 0.03 & 30 respectively.
Abrams, (1975)	To study changes in IFT, viscosity, flow rates after mixing chemicals with the water	Chemical dissolved water, oil	• A short core is wetted with water and then oil. • The oil is displaced with a chemical added water.	• Oil recovery increased with decrease in IFT, increase in viscosity by adding some chemicals. • Equation developed for efficient recovery considers viscous & capillary forces, viscosities ratios & required concentration and amount of polymer.
Daripa & Pasa, (2005)	To find an optimal /intermediate µ fluid b/w oil and water in the 2 and 3 layers systems	Polymer solution, oil and water	• In 2 layers fluids, injection of water and oil (middle layer has variable viscosity) • In three layers system, water is injected after polymers (polysolution) which has low viscosity at water side but high at oil side.	• Intermediate layer controlled the viscosity jump which controlled oil recovery • Viscous fingering reduced oil recovery considerably. • Polymer reduced IFT between water and oil and increases oil recovery
Wassmuth et al., (2009)	To observe polymer recovery from a rock sample	Polymer solution and oil	• A core sample taken from East Bodo reservoir is flooded with water cut upto 95% before polymer injection.	• The polymer enhanced incremental oil recovery by 20%OOIP after water flooding.

Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
Hematpour et al., (2011)	To study the effects of polymer types on the displacement of low viscous oil	Different polymers and less viscous oil	• 2 simplified glass micromodels were used. • The oil saturated cells were flooded with three different polymers with a constant flow rate of 0.0008 cc/min.	• Polymer reduced mobility of water • Hydrolyzed polyacrylamide (25%) yields more recovery than other polymers. • Low flow rates, yield less fingering and high recovery.
Ying-jie et al., (2013)	To analyse effects of pore structures on polymer and reservoir brine flooding in glass micromodel	Polymer solution with synthetic reservoir brine and oil	• They etched glass model (3×2×0.04cm) which represented a sample of an oil field. • The heterogeneous reservoir and 95% water cut was flooded initially by water at constant flow rate and then by polymer solutions. Polymer ($Mv=400x10^4$)	• Water bypassed the narrow channels and flew through the large pores/channels. • Pore throat ratio effected recovery more than the coordination number because higher PTR, means more heterogeneity, less CN and low recovery. • Polymer increased oil recovery in all models.

4.2.4. Nanocrystals and its Application in the Oil Industry

Nanocellulose/nanocrystal is explored for use in oil recovery processes. Azizi Samir et al., (2005) reported on the potentials of nanocellulose in plastic, automotive, railway, aircraft, furniture, and sports industries due to its renewable nature, availability, low cost, reduced energy consumption, strength and easy processability.

On adding nanocellulose to water, the aqueous phase viscosity rises and ithe interfacial tension between the aqueous phase and oil drops (Zhang 2010; Salas et al., 2014). It is observed that nanocrystals help in forming a stable emulsion (Zhang et al., 2010). The emulsion can control mobility of the phases and enhances oil recovery from the reservoirs (Zhang et al., 2010). Nanoparticles, due to their smaller sizes can easily flow through pore spaces in the reservoirs without much retention on the rock surface. Fleming et al., (2001); Habibi et al., (2010), and Xhanari et al., (2011) reported on stability of oil-water emulsions after adding cellulose nanocrystals to the system. Xhanari et al., (2011) concluded that the emulsion of water and oil in the presence of microfibrillated cellulose remained stable for more than one year and this stability is achieved by the network of microfibrillated cellulose that forms on the interface of oil and water. Zhang et al. further explained that wettability and adsorption of surfaces could be controlled by adding Silanol groups to either the nanoparticles or the surface, which alters the nanoparticle's surface to be more hydrophilic and increases stability of oil in the water emulsion. Due to higher stability of the emulsion, nanoparticles are mainly used in drilling industry. Zhang et al., (2010) prepared different emulsions with nanoparticles coated by different surface coatings and analysed their stability. They concluded that the emulsions with 0.5 weight percent or higher are stable remaining intact for time scales of order of months. They concluded that the average droplet size in the emulsion decreases with the increase in concentration of the nanoparticles. Some of the research conducted in the field of nanofluids/nanocrystals and its application in oil industry is listed in Table 5. For the oil industry, the use of nanocrystals is reported by Lenk et al., (1992); Westland et al., (1994); Wasan and Nikoloy, (2003); Rodriguez et al., (2009), Wu et a., (2012); Cheraghian et al., (2013); Rincon et al., (2013), and Lafitte et al., (2013). Majority of the published studies explored applications of nanocrystals for increasing stability of drilling fluids, reducing friction losses in casings, and drilling tools, reinforcing geological formations, and increasing oil recovery.

Table 5. Summary of the nanocrystals use in the oil industry

Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
Lenk et al., (1992)	To study rheological properties of the drilling fluids	Nanocrystals in drilling mud	• Nano crystals are added to the drilling fluid	• The nanocrystals enhanced rheological properties of the drilling mud/fluids
Westland et al. (1994)	To study nanofluids for use in oil industry	Drilling mud	• The nanoparticles in mud are investigated for stability of the solution and formations	• Friction losses in casings reduced, geological formations became stronger with the nanocrystals.
Wasan and Nikoloy, (2003)	To study oil recovery from nanochannels	Oil-nanoparticles	• Nanochannels created and recovered oil from them	• The oil water flow increased through the nanochannels • The oil recovery increased
Rodriguez et al., (2009)	To study two types of nanocrystals in oil recovery	Drilling fluids, nanofluids	• Nanoparticles coated with polymer • Cores of limestone and sandstones are flooded with the nanofluids	• Polymer reduced its adsorption on surfaces • No slip condition is no more valid, due to movement of particles along the surface • Viscosity of the fluids and oil recovery increased
Kalashnikova et al., (2011)	Microscopic study of oil water interface and nanoparticles emulsion	Oil, nanofluids	• Microscopic and SEM study of bacterial cellulose nanocrystals (70%) and oil (30%)	• Oil droplet remained in suspension for 7 months unless disturbed • Stability of interface increases and droplet sizes decreased with increase in concentration

Reference	Objectives	Fluids Used	Experimental Set up and Method	Findings
Wu et al., (2012)	Microscopic study of nanoparticles movement in the oil-water on surface	Oil, water and nanoparticles	• Microscopically followed the nanoparticles • Study the oil/water interface	• Nanoparticles adsorbed on the clay surface. • Oil dispersed in the water • Oil recovery increased with increase in viscosity and reduction in interfacial tension.
Cheraghian et al., (2013)	To study nanofluids in drilling and recovery	Drilling fluids, nanofluids oil	• Two types of nanoparticles are used • They are added to the drilling fluids • Study its movement	• The nanoparticles increased oil recovery, altered the surface water wet, improved mobility, increased yield point of the drilling fluids and its velocity. • Suspension of drill cuttings in the mud increased.
Lafitte et al., (2013)	To compare nanofluids and polymer	Nanofluids, oil	• Checked the use of nanofluids for oil recovery	• The nanofluids increased oil recovery same as polymer. • It could be a better replacement of polymers
Rincon et al., (2013)	To use nanocrystals for fracturing and cementations	Cement, water	• Addition of nanocrystals to the cement slurry • Addition of nanocrystals to the fracturing fluid	• The cement strength and packing increased • The fracturing efficiency increased • Viscosity increased with nanocrystals

5. Phase Interference in Multiphase Flow Through Gap

Previous works on multiphase flows in Hele-Shaw cells are mainly focused on the displacement of one phase by another phase. Most of these studies used Hele-Shaw cell as a visual porous medium prototype to understand enhanced oil recovery mechanisms using water and additives. On the other hand, for flow patterns studies, many experiments dealt with the gas-liquid, i.e., air-water, systems. Currently, there are a few studies reporting the flow structures in co-current flow of oil and other solutions. This is of importance to oil recovery from fractured reservoirs, as there is a continuous feed of oil and formation water from matrix blocks and injected solutions into the fractures. Thus, simultaneous flows of oil and other solutions encountered in fractures, narrow gaps between two matrix blocks. Furthermore, a few researchers examine the impact of new materials such as nanocrystal suspensions for oil recovery.

In order to fill this gap and analyse thoroughly the two-phase flow of oil with other solutions through thin gaps, the authors of this paper conducted experimental examination of oil flow with water, surfactant, polymer and nanocrystals solutions in a thin gap in Hele-Shaw Cell. This was PhD research work of Salim Raza at University of Calgary, Canada. The research examines flow structures, phase interference, and microscale imaging to understand the dynamics of multiphase flow within a narrow gap, an idealized model of a fracture. In this research it was concluded that in the case of water oil flow, different flow regimes form with change in flow rates and breakthrough time. Linear displacement of oil and water saturation in the form of a thick single finger are witnessed prior to water breakthrough, but after breakthrough and further increase in the water injection rate, the water fingers at the tip and sides, resulted in reduction in water saturation with creation of unstable interfaces. This phenomenon reveals, that for the subsurface oil recovery applications such as water flooding, if the water rate remains constant, the oil recovery will be low which may increase with the increase in the water flow rates. The results were also analysed and confirmed through relative permeability curves and the capillary number for the two phases which was less than unity shows the higher interfacial tension between water and oil (Raza et al., 2016). In the next stage of the research, surfactant, polymer and nanocrystals solution were co-injected with oil through the cell with the aim to enhance oil recovery from the cell. Papers of surfactant and polymer are in publication stages, however the nano particles aqueous flow through the oil saturated cell is published in Raza et al., (2021). In this part of the research, aqueous phase of Cellulose nanocrystals (CNC) is used for displacing oil from a fracture. It was observed that CNC raises the viscosity lowers the interfacial tension with oil. It was observed that the nanofluid forms more stable fingers which grow with increase in flow rates and displace oil more efficiently than water, surfactant and polymer. Microscopic study shows engulfment of the oil in the form of emulsion at the interfaces of the two phases. Relative permeabilities of the phases shows more than 90% oil recovery from the cell by CNC, concludes that it can be effectively used for oil recovery from fractured rocks.

6. Conclusions

Petroleum reservoirs deplete rapidly in the world and the researchers now focus on how to increase production from the existing reservoirs and start production from the fractured rocks, which host a huge proportion oil. The purpose of this review paper is to highlight various studies for multiphase flow in different conditions and focus on the oil recovery from fractured and heterogeneous rocks. Initially multiphase flow through pipes is studied by different researchers and majority of them focussed on the study of the flow regimes and instabilities created in the flow of water and air. The studies reveal that the flow patterns in different fluids depend upon superficial velocities of fluids. Majority of the researchers classified flow patterns as water drops in oil, oil in water concentric, oil slugs in water, elongated bubble, oil bubbles in water, oil drops in water, stratified wavy, stratified wavy with drops, three layers and stratified mixed patterns.

Multiphase flow through narrow gaps is also studied by various researchers. Majority of them focussed on air-water flow through these gaps, whereas a few focussed on water oil, surfactant oil and polymer oil flow through thin gaps or fractured media. Again, most of them focussed on the study of the flow patterns at various conditions. They concluded that the viscosities of the fluids, orientation of the fractures, roughness of the fracture walls, and interfacial behaviours of the displacing and displaced fluids mainly affect the flow patterns and mobilities of the fluids. Majority of the circumstances could not typically reflect the reservoir conditions, however, a thorough experimental study is done by Salim Raza in his PhD research work to model most of the fractured reservoir conditions and displaced oil by water, surfactant, polymer and nanofluids. Flow patterns and recovery from the fracture is studied thoroughly. Experiments showed that more stable flow patterns form as the displacing phase is changed from water to surfactant, polymer and more effectively nanofluids, which yielded maximum oil recovery than the other fluids. It can be concluded that for efficient oil recovery from a hydrophobic fractured rock, nanofluids could be efficiently used.

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