Petroleum and Coal

Article Open Access

Conceptual Modelling of Low Salinity Water Flooding in a Fractured Reservoir

Suresh Kumar Govindarajan[1], Abhishek Kumar[2], Avanish Mishra[2], T. N. Venkata Pavan[2]*

[1] *Reservoir Simulation Laboratory, Petroleum Engineering Programme, Department of Ocean Engineering, Indian Institute of Technology – Madras, Chennai, India*

[2] *Reservoir Simulation laboratory, Petroleum Engineering Programme, Department of Ocean Engineering, Indian Institute of Technology – Madras, Chennai, India*

Received July 10, 2019; Accepted September 29, 2020

Abstract

Low Salinity Water Flooding (LSWF) is an improved water flooding technique that enhances the oil recovery with a relatively cheaper cost. Such technique becomes vital as the oil price keeps falling significantly at the global scale. Although plenty of research work has been devoted towards LSWF in conventional sandstone reservoirs, the research on LSWF in fractured reservoirs is still at its beginning stage and a lot needs to be explored in this direction. In this context, an attempt has been made in order to deduce the conceptual model that will describe the mechanism of LSWF in a fractured aquifer using dual-porosity approach. Unlike the conventional sandstone reservoirs, which are based on single-continuum concept, the fractured reservoirs are associated with a multi-continuum based concept and hence, the mechanism of LSWF still becomes complex. Two different types of conceptual models have been proposed in the work. The mechanism of LSWF technique takes place only within the low-permeable rock-matrix, while the high-permeable fracture just acts as a conduit and carries the released oil towards the production well in Model 1. However, in Model 2, the mechanism of LSWF technique takes place both within the low-permeable rock-matrix as well as on walls of the high-permeable fracture. In this context, a detailed list of possible queries that may arise during the experimental/field investigations of LSWF in a fractured reservoir has been discussed in detail. This work is expected to provide further insights for carrying out the LSWF in a complex fractured reservoir.

Keywords: *Low salinity; Water flooding; Conceptual model; Mathematical model; Fractured reservoir.*

1. Introduction

Due to the enhanced increment in energy consumption at the global-scale, various methods of energy resources are required in order to successfully meet the global energy growth as well as demand. The role of fossil fuels would remain inevitable at least for the next few decades in meeting these elevated global energy demand. It is well known that the global extraction of oil from petroleum reservoirs is nearing about 30%, while the rest of it, i.e., nearly 70% of the Original Oil in Place (OOIP) remains trapped in oil reservoirs. It can be noted that the efficiency primary and secondary oil recovery processes remains conditional as a function of initial average reservoir pressure and the compressibility characteristics of the concerned reservoir fluids. Thus, in conventional sandstone reservoirs, nearly two third of the OOIP is trapped due to the complex chemical equilibrium associated with the in-situ crude oil, reservoir formation water and the reservoir's fluid-rock interaction that includes the rock wettability; the interfacial tension; and the capillary pressure. The presence of heterogeneity as well as the nature of oil-wet makes the oil extraction even from conventional sandstone reservoirs to be very difficult. In addition, when the oil extraction is associated with a fractured reservoir, the complexity becomes multi-fold. In general, the fractured reservoirs are characterized by the multiple continuums as against the conventional single-continuum approaches. However, the fluid flow through fractured reservoirs are so complex in nature and it requires a large number of operational parameters in order to have a better control over an enhanced oil recovery unlike the conventional sandstone reservoirs. The fundamental problem associated with a fractured reservoir is that the low-permeable rock matrix stores all of the oil reserves, while the high-permeability fractures serves as a conduit in order to transmit the mobilized oil towards the production well. Thus, in a fractured reservoir, the fluid flow mechanism is fundamentally distinct from that from a sandstone reservoir, where the fluid storage as well as the transmission takes place at the same location. The oil extraction using Enhanced Oil Recovery (EOR) methods have generally yielded an increased oil recovery [1-15] but at the expense of an enhanced investment. Thus, the concept of cost-effectiveness plays a crucial role in extracting the oil from mature fields using secondary and tertiary recovery methods. In this context, it is essential to follow the method that will yield an enhanced oil recovery, while the associated cost should be significantly less in comparison with the other Improved Oil Recovery (IOR) techniques. Low Salinity Water Flooding (LSWF) is an improved form of water-flooding with a relatively lower-cost technique used in the field widely [16-24]. Mostly, in LSWF, the vastly available sea water with a well-controlled salinity is used in order to introduce the wettability reversal from oil- to water-wet; and subsequently to enhance the migration of fines leading to an enhanced production of crude oil. However, it is to be noted that the LSWF technique has been explored significantly in conventional sandstone reservoirs, while the mechanism of LSWF in a fractured reservoir remains poorly understood and deserves special attention for further investigation. In this context, the objective of the present manuscript is to deduce the conceptual modelling of LSWF associated with a fractured reservoir using dual-porosity approach; and also, to deduce its associated complexities. This study aims to investigate the feasibility of using LSWF technique in a typical multi-continuum reservoir using a dual porosity approach by mitigating the water production following the breakthrough of the low-saline injected brines.

2. Low salinity water flooding

Water-flooding is a typical secondary recovery method that is used to maintain the (lost) initial reservoir pressure; and subsequently to maintain the reservoir pressure to be at a level that is greater than the bubble-point pressure so that the dominant viscous forces drive the trapped residual oil towards the production well; and thereby improving the sweep efficiency of the reservoir. In general, the efficiency of a secondary recovery method using water-flooding technique is critically influenced by reservoir rock properties (porosity, permeability, aerial and vertical heterogeneity); reservoir fluid properties (connate-water and viscosity); and the mineralogical properties (the amount of swelling clay contents). However recent studies on water flooding have practiced a varying chemical composition to the injected brine, which subsequently disturb the established chemical equilibrium of the reservoir fluids; and in turn, yield in an enhanced oil production. Such usage of smart water that is used to enhance the oil recovery is widely known as the LSWF technique, which essentially involves the controlling on the chemical salinity and the mineralogical composition of the injected brine water. This technique is relatively cheaper and environmental-friendly in comparison with the conventional high-salinity water flooding and other Enhanced Oil Recovery (EOR) processes. The presence of clay particles in the reservoir formation; and the presence of divalent cat-ions in the connate water (calcium and magnesium cations can lead to oil-cation-oil; oil-cation-mineral; & mineral-cation-mineral interactions) are very critical for the successful LSWF technique, while the crude oil should contain the acids and bases (the polar interaction between the polar functional group of oil and the polar mineral solid surface sites). Martin [25] and Bernard [26] were the earliest authors to modify the composition of the injected brine and subsequently they proved that the same mechanism resulted in an Improved Oil Recovery (IOR). Tang and Morrow [27] concluded that the release of mixed-wet fine particles (with attached oil droplets) from the solid surface grains helped in improving the oil recovery, while the same release also paved the way for the wettability reversal from oil-wet to more water-wet. Simultaneously, British Petroleum successfully injected the low saline brine with less than 3000 ppm in a clastic reservoir and this LSWF technique was able to mitigate the residual oil saturation significantly in a field trial. McGuire [28] noticed the enhancement in the pH value of the formation fluid following the injection of LSWF; and the subsequent generation of hydroxyl ions during the interaction of low salinity injected brine with the in-situ (reservoir) formation fluid (connate-water). The increased pH value not only helped in reducing the interfacial tension by acting as a surfactant (the polar components in the oil gets saponified, when the oil gets in contact with the high pH – low-saline brine) but also in reversing the rock wettability from oil-wet to more water-wet. Lager [29] concluded that Multi-component Ion Exchange (MIE) [between the crude-oil, rock-surface and the brine] takes place during the LSWF process that improves the oil recovery. In general, the efficiency of the LSWF technique can be enhanced by altering the chemical composition of the injected brine; and in particular, by reducing the salinity of the injected bring to be between 1000 and 5000 ppm (as against the reservoir formation salinity of around 2,00,000 ppm and sea-water salinity of around 35,000 ppm) with the optimal ionic composition that significantly diminishes the residual oil saturation. However, it can be noted that the enhancement in oil recovery remains conditional upon reducing the salinity of the injected brine; on the presence of multivalent ions in the formation brine; and on the presence of swelling clay minerals within the sandstone reservoir formation. The LSWF technique involves wettability alteration (measurement of fluid contact angles before and after the injection of low saline brine); the reduction in Inter Facial Tension (IFT) between the crude-oil and the brine; fluid pH; zeta potential of mineral surfaces; the Cation-Exchange-Capacity (CEC); the adsorption isotherms; and the imaging of the solid mineral surfaces at different scales. And, the analysis becomes further complicated for a fractured reservoir in order to deduce the optimum value of the injected brine composition for a coupled fracture-matrix system, where the interaction between stored immobile crude oil and the formation brine within the low-permeable rock matrix; and the interaction between mobile crude oil and the formation brine within the high-permeable fracture dictates the resultant efficiency associated with the LSWF. Thus, the conceptualization itself becomes very critical in a fractured reservoir that describes the successful LSWF technique.

3. Physical system and conceptual model of LSWF

A fractured reservoir fundamentally differs from that of a sandstone reservoir in the sense that the storage and transmissivity in a fractured reservoir takes place in two different fundamental entities namely 'fracture' and rock-matrix', while both the storage as well as transmissivity in a sandstone reservoir takes place at the same pore-space. The high permeable fractures act as conduits.

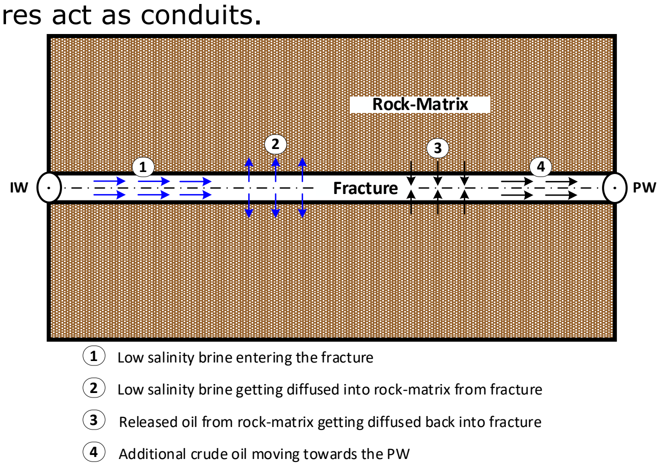

Fig. 1. Conceptual model of LSWF mechanism in a fractured reservoir using dual-porosity approach

All the trapped residual oil has been stored within the low-permeable rock-matrix. In LSWF technique, the low saline brine will be injected through an Injection Well (IW). The brine would first reach the high-permeable fracture. Since, the permeability of the fractures are relatively high, the advective forces will drive the low saline brine within the fracture along the flow direction from the injection well (IW) as shown in Fig 1 and this process is represented as (1) in Fig 1; and it is represented as horizontal arrows nearer to the Injection Well (IW).

During the travel along the flow direction, the low saline brine will also get transported in a direction perpendicular to the basic fluid flow direction as shown as (2) in Fig 1 and it is indicated by vertical upward arrows at the fracture-matrix interface. The fluid mass exchange in this direction involves the transfer of injected low saline brine from the fracture into the rock-matrix either by diffusive means (for very tight rocks) or by advective means (if the rock-matrix is having significant permeability). Once, the low saline brine gets diffused into the rock-matrix, then, the actual effect of LSWF technique starts. Fractures will be having 100% porosity at the scale of a single-fracture, while the concept of 'fracture-porosity' refers to the ratio between the pore-volume occupied by the fractures to the total bulk rock volume. The porosity and permeability of rock-matrix will be much smaller than the porosity and permeability of a single fracture. The LSWF technique is expected to reduce the residual oil saturation within the rock-matrix; and in turn, the released residual oil will get transported back from the rock-matrix into the fractures as shown as (3) in Fig 1 and the same is indicated as vertical downward arrows at the fracture-matrix interface. Having reached the fractures, these released oil components will be transported towards the production well as shown as (4) in Fig 1 and it is represented as horizontal arrows nearer to the production well (PW). In the present work, the authors have made an attempt to investigate the feasibility of low salinity effect in a fracture reservoir using dual-porosity approach [30-69]. For conventional sandstone reservoirs, the salinity of the injected water is maintained at a rate of less than 5- 6 g/l, while the optimum range hangs around 1 -2 g/L. However, in a fractured reservoir this rate would vary significantly as it will be a strong function of fracture and rock-matrix parameters. The low permeable rock-matrix should be associated with a significant amount of sensitive clay minerals associated with the formation water and enough divalent ions, while the crude oil is supposed to contain a significant amount of polar compounds.

Upon the diffusion of the low saline brine into the low-permeable rock-matrix, the electrostatic forces will be weakened; and it essentially disturbs the equilibrium of the attached particles on the solid surfaces of the mineral rock grain. Initially, these fine particles were in 'mechanical equilibrium' that consisted of drag force, lift force, electro-static force and gravitational forces. Once the equilibrium is disturbed, the initially attached fine particles get detached from the solid surface and find its way within the pore-spaces. Now, these fine particles are getting dragged within the rock-matrix pore volume. During this process, these fine particles may clog the narrow pore throats and subsequently, may further reduce the rock-matrix permeability. In a fractured reservoir, the permeability reduction within the rock-matrix may be very significant resulting from the injection of low saline brine and it may reduce the rock-matrix permeability by about 100 – 1000 times from its initial value. The problem becomes very complex here in the sense that the detached oil droplets requires some minimum threshold rock-matrix permeability in order for its effective mobility towards the fracture.

It can however be noted that the attaching torque (gravitational force and electrostatic forces) should be less than or equal to the detaching torque (drag and life forces) for the fine particles to remain on the solid rock-matrix grain surface so that the condition of 'mechanical equilibrium' is satisfied. Otherwise, the hydrodynamic forces (i.e., the drag force and the lift force) will tend to release these adsorbed fine particles. These hydrodynamic forces depend on the fluid flow velocity, while the electrostatic forces (which is the summation of van der Waals, electrical double layer and Born forces) remains a function of the compositions of fine-particles as well as the rock-mineralogy apart from the composition of the in-situ fluid (pH, salinity and temperature). Thus, either the fluid velocity or fluid chemistry may disturb the equilibrium between the attaching and detaching torques; and subsequently, the initially adsorbed fine particles will get released. Following the release, the hydrodynamic forces drive the fine-particles as the presence/injection of low saline brine suppresses the electrostatic force. Finally, these released droplets get transported from rock-matrix into high permeable fracture.

Figure 2 represents the sensitivity of the rock mineral surfaces containing the clay contents (which contain a sheet of tetrahedral silica and octahedral aluminium layers and producing structural imbalances in either of them apart from the presence of negatively charged particles on the edges) within the low permeability rock-matrix that lead to an enhancement in the oil recovery. Thus, the clay surfaces within the rock-matrix remain in an unstable condition as shown in Fig 2a. Thus, upon the intrusion of low saline brine within the low-permeable rock-matrix, a new chemical equilibrium is established under the real reservoir conditions as a function of reservoir pressure, reservoir temperature & pH of the formation fluid.

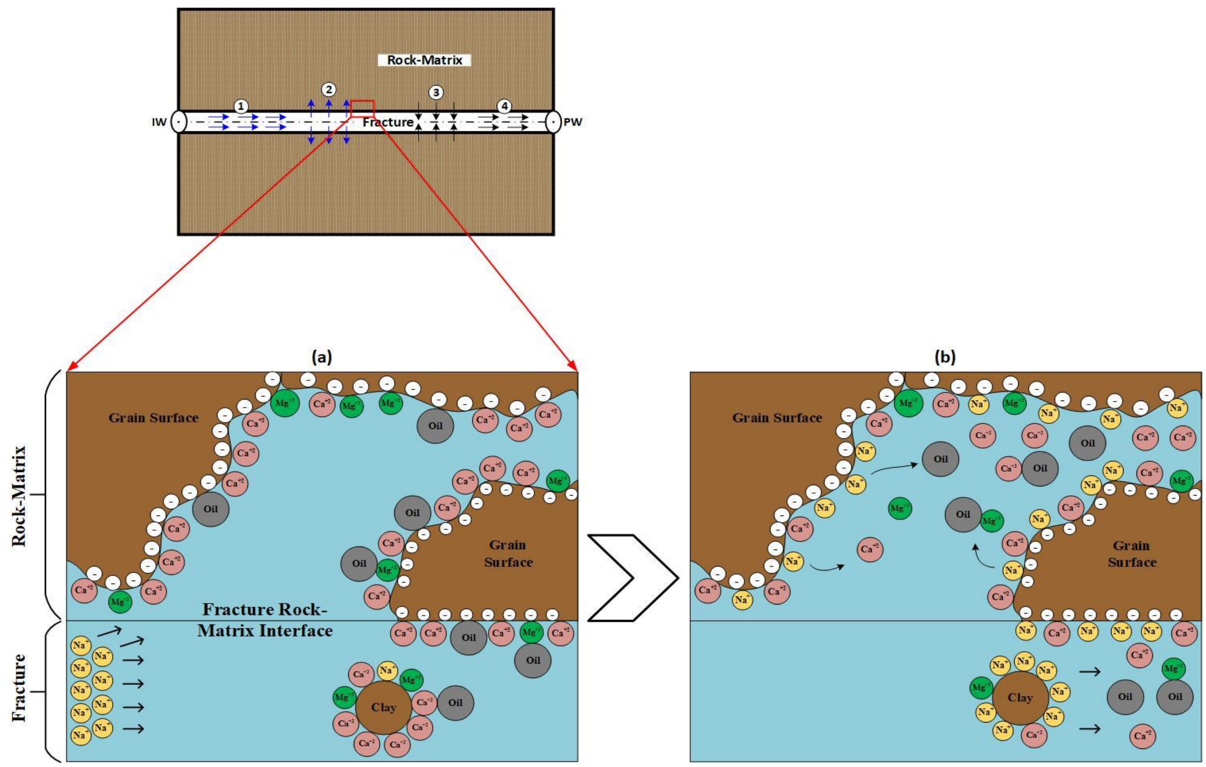

Fig. 2. Multicomponent ion exchange phenomenon in a coupled fracture-matrix system (a) before the injection of low saline brine near the Injection Well (IW) and (b) after the injection of low saline brine towards the production well

This new chemical equilibrium essentially disturbs the already existing rock-brine equilibrium; and subsequently, this disturbance lead to a resultant desorption of divalent cations, particularly calcium and magnesium ions. Hence, for a given pH, these clay surfaces tend to attract these desorbed Ca^{2+} and Mg^{2+} divalent cat-ions (the maximum value pertains to cation exchange capacity) from its surrounding pore volume in order to neutralise the unstable charges. Thus, it can be observed from Fig 2b that the oil components get released from the ionic exchange process; and subsequently, the pore fluid within the rock-matrix tends to have more and more released oil components. These pore fluids containing the enhanced oil against the water slowly get transported towards the high permeable fracture either by concentration gradient or by advective forces depending on the permeability of the rock-matrix. Once, the oil pool reaches the high permeable fracture, they are being advected towards the production well; and subsequently enhancing the oil recovery. In addition, there will be an addition of protons from the formation fluid on the clay surfaces in order to compensate the desorbed divalent cations; and eventually leads to an enhancement in pH close to the clay surfaces. This enhancement in pH also paves way for the enhanced oil recovery. However, it is not clear whether how these mechanisms will happen at the fracture-matrix interface as there is a migration of low saline brine from fracture to matrix; along with the migration of released oil from the rock-matrix to the fracture in the opposite direction. Also, the fraction of the fracture length along which these fluid mass transfer takes place between the fracture and the rock-matrix will be very critical in deciding the resultant additional oil recovery.

Upon the injection of low saline brine into a fractured reservoir, once the low saline brine gets diffused into low-permeable rock-matrix from the high-permeable fracture, it influences the electrical charges at the oil-brine interfaces within the rock-matrix; and subsequently causes the expansion of the double layer (consists of an inner adsorbed layer with positive ions along with an outer diffusive layer of dominant negatively charged ions as shown in Fig 3).

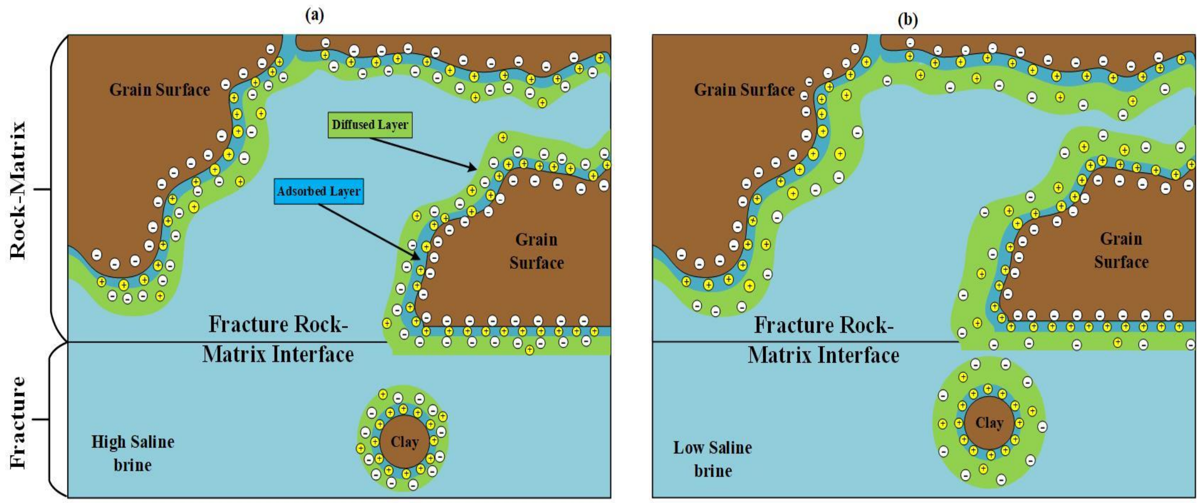

Fig. 3. Impact on the electrical double layer expansion (a) Before LSWF near the IW with high saline formation water (b) Expansion of double layer due to LWSF in a coupled fracture-matrix system

The inner adsorbed layer contains divalent cations such as Calcium and Magnesium, which essentially act as tethers in between the clay-mineral and the oil-component. Upon the injection of low saline brine, the diffusive layer gets opened. And, as a result monovalent ions such as Sodium displaces these divalent ions; and subsequently, the electrostatic repulsive forces between the clay-minerals and the oil components starts increasing. When these increasing repulsive forces become significantly larger, the tethers between the clay-minerals and oil-components get broken; and thus, the oil-components are getting desorbed from the clay-minerals; and leads to the reversal of wettability; and in turn enhancing the oil recovery [70]. However, it should be noted that the electrical surface charges depends on the pH of the low saline brine. In addition, the thickness of the electrical double layer is a function of electrical charges that exists between mineral-brine and oil-brine interfaces. The value of the 'Zeta potential' (the potential that exists at the shear plane of the electrical double layer) needs to be measured at the mineral-brine and oil-brine interfaces for varying pH values along with the measurement of the contact angle in order to find how exactly the initially more oil-wet reservoir gets transformed into a more water-wet reservoir by releasing the oil components from the mineral and brine surfaces as shown in Fig 3. However, these measurements within the low-permeable rock-matrix remains challenging. Further, crude oils remains positively charged at lower pH values; and hence, it is mandatory to ensure that the crude oil remains negatively charged for an efficient low salinity effect. It is not clear whether the potential of a low saline brine injection into a fractured reservoir would remain potential by both secondary injection as well as tertiary mode.

The concept of LSWF mechanism in a fractured reservoir can be conceptualized using 2 different models. In Model 1, it can be assumed that all the low salinity effect is taken place within the low-permeable rock-matrix, while the fracture is treated only as a conduit that collects the additional oil recovery resulting from the low salinity effect associated with the rock-matrix. In Model 2, it can be assumed that the low salinity effect is taken place in both high-permeable fracture as well as low-permeable rock-matrix. The Model 1 will be more realistic as the low-permeable rock-matrix is similar to a porous medium; and subsequently, all the mechanism of low salinity effect can be expected to happen within the rock-matrix only. The distinction between Models 1 and 2 have been tabulated in Table 1.

Table 1. Injection of low saline brine in a fractured reservoir using Models 1 and 2

Model 1	Model 2
The flow rate of the injected low saline brine is adjusted in such a way that it diffuses into rock-matrix significantly.	The flow rate of the injected low saline brine is adjusted in such a way that it diffuses into rock-matrix significantly, while it gets advected within the high-permeable fracture.
The additional oil recovery resulting from low salinity effect takes place only within the rock-matrix.	The additional oil recovery resulting from low salinity effect takes place in both the rock-matrix as well as on the fracture walls.
The presence of clay mineral surfaces is expected only within the rock-matrix.	The presence of clay mineral surfaces is expected in both rock-matrix and on the fracture walls.
A relatively larger additional oil recovery can be expected from the low salinity effect associated with the rock-matrix.	A relatively smaller additional oil recovery can be expected from the low salinity effect associated with the fracture.
More realistic as the fracture-matrix interface nearer to the IW can be assumed to be involved in the diffusion of the injected low saline brine into rock-matrix, while the fraction of the interface towards the PW can be assumed for the mass transfer of the released oil into the fracture.	The fluid mass transfer process at the fracture-matrix interface is too complicated as both the fracture and matrix are involved in producing the additional oil resulting from the low salinity effect.

4. Discussion on complexities associated with LSWF

1. How to estimate the diffusive mass transfer of injected low saline brine from high-permeable fracture into low-permeable rock-matrix?
2. What will be the time required by the injected low saline brines in order to get diffused into low-permeable rock-matrix from high-permeable fractures? Can this diffusive mass transfer be assumed to be one-dimensional?
3. What would be the optimal fracture and matrix parameters in order to deduce a significant increase in pressure drop within the high-permeable fracture (along the flow direction) for the given residual oil saturation associated with the low-permeable rock matrix; and that enhances the resultant reservoir oil recovery or that reduces the residual oil saturation present in the rock-matrix?
4. What would be the optimal amount of clay content that is expected within the low-permeable rock-matrix and on the fracture walls that will enhance the resultant oil recovery?
5. Will it be feasible to observe the low salinity effect within the fractures in the absence of clay minerals but with the surface properties of the fracture wall been modified by a chemical agent by other than the conventional clay minerals such as 'organic materials'?
6. What should be the optimal amount of mono- and divalent-ions that should be associated with the injection brine with reference to the composition of the rock-matrix formation brine?
7. Will it be feasible by the low permeable rock-matrix clay particles to get detached and mobilised with the oil by an enhanced adhesion of polar oil components to rock-clay minerals during the low salinity injection?
8. Will the adhesion of crude oils on the fracture surfaces or on the solid matrix grains within the low permeable rock-matrix would remain pH dependent during the injection of low salinity brine – following the DLVO theory that determines the colloidal stability using electrostatic and van der Waals forces? If so, under what circumstances?
9. Will the injected low salinity brine into a coupled fracture-matrix system would first invade the entire fracture or will it invade both fracture as well as rock-matrix first simultaneous?
10. Having diffused into the low-permeable rock-matrix, will the injected low salinity brine displace the oil from the smallest water-wet pores to the largest water-wet pores; and then, displace the oil from the largest oil-wet to the smallest oil-wet pores OR the vice-versa? Will the capillary entry pressure within the low-permeable rock-matrix always remain larger than the driving pressure?

11. Having diffused into the low-permeable rock-matrix, will the injected low salinity brine try to reduce the contact angle; and in turn, will decrease the capillary entry pressure of the oil-wet pores? Will it subsequently lead to the displacement of oil from the smallest pores associated with the rock-matrix?
12. In a coupled fracture-matrix system, do we still need to reduce the salinity of injected brine to be under 5000 ppm; or even a relatively higher salinity will lead to wettability reversal; and in turn, will reduce the residual oil saturation? Will it be feasible to deduce the threshold value for the lower salinity for a fractured reservoir?
13. Having diffused into the low-permeable rock-matrix, will the injected low salinity brine be able to reduce the residual oil saturation within the rock-matrix in the absence of multivalent ions in the formation water associated with the rock-matrix? Will those ions that were initially adsorbed onto the solid mineral surfaces within the rock-matrix be sufficient to initiate wettability reversal; and in turn, to reduce the residual oil saturation?
14. What should be the optimal initial pH; and in turn, the optimal initial brine saturation within the low-permeable rock-matrix that will promote the adsorption of polar oil compounds; and in turn, will facilitate the wettability reversal?
15. Is there a way to estimate or measure the "enhanced pressure drop" within the low-permeable rock-matrix resulting from the injection of low salinity brine into a coupled fracture-matrix system?
16. Rock-matrix being very tight (having negligible porosity and permeability), will it be feasible for the low salinity brine to lead to wettability reversal in the absence of producing fines; and its subsequent fines migration? Will it further reduce the permeability of the rock-matrix? If so, will the fluid mass transfer from rock-matrix to fracture will further get mitigated?
17. Having diffused into the low-permeable rock-matrix, will the injected low salinity brine be able to alter the pH value to be greater than 9 (with its corresponding elevated acid number) that will facilitate the saponification?
18. Will the diffusion of low saline brine from the fracture into the rock-matrix would facilitate the adsorption of divalent ions on the rock-mineral clay surfaces; and thereby releasing the already adsorbed oils?
19. Will it be feasible to estimate the dilution of the injected saline brine that facilitates the desorption of divalent ions within the rock-matrix?
20. Will it be feasible to estimate or measure the enhanced pH values within the low-permeable rock-matrix and high-permeable fracture explicitly upon the injection of low saline brine?
21. Will it be feasible to capture; and subsequently to estimate or measure the expansion of electrical double layer at the mineral-brine surfaces within the low-permeable rock-matrix and on the fracture walls within the high-permeable fracture explicitly upon the injection of low saline brine? Whether the enhanced electrostatic repulsion between the charged rock-mineral surfaces and the adsorbed polar oil components within the high-permeable fracture and low-permeable rock-matrix would remain the same? If not, what would be the possible reasons?
22. How exactly the variation in the thicknesses of the diffusive part of the electrical double layer; and the 'zeta potential' will vary within the low-permeable rock-matrix and on the fracture walls within the high-permeable fracture explicitly upon the injection of low saline brine?
23. What should be the optimal injection rate of brine salinity into the high-permeable fracture that leads to desorption of oil and its subsequent wettability alteration, while preventing the onset of fines release and its associated formation damage?
24. Will the injection of low saline brine into a fractured reservoir would lead to a favourable shift in relative permeability curves and its associated enhanced oil recovery? It should be clearly noted whether the 'initial crude oil permeability' at connate water saturation is used; or the 'permeability of the brine' is used for normalizing the relative permeability curves – apart from the variations in results that is associated with the procedure on initializing the cores and its associated 'aging time'.

25. Having diffused into the low-permeable rock-matrix, how long will the injected low salinity brine will consume to release the trapped oil? What will be approximate time-scale required for desorption/detachment, coalescence; and its subsequent diffusive/advective transportation of oil droplets from the low-permeable rock-matrix into high-permeable fracture?
26. Whether the modification on the ionic content of the injected brine has a direct/inverse correlation with the thickness of the fracture aperture and the fracture spacing?
27. What would be enhancement in oil recovery resulting from a LSWF associated with a fractured reservoir?
28. Whether the nature and intensity of variations associated with the adhesive forces and the resultant release/desorption of oil components from the solid surfaces of rock-matrix and from that of the fracture walls would remain the same? If not, what could be the possible parameters that control the changes in adhesive forces upon injection of low saline brine in a fractured reservoir?
29. Will it be feasible to capture the variations in contact angles and its associated interface curvatures within the low-permeable rock-matrix upon the injection of low saline brine?
30. Assuming that the concept of "initially wettability state" dictates the resultant nature of low salinity effect within the low-permeable rock-matrix, how will it feasible to translate such sub-pore scale wettability effect into a larger continuum-scale associated with the Representative Elementary Volume (REV)?
31. How far, the breakthrough time will get delayed for the low saline brine injection in a fractured reservoir? How will the profile of water-cut behave at the producing well? Can the reservoir response from the injection of low saline brine be successfully modelled using Buckley-Leverett analysis? Would it lead to a significant variation in the resultant fractional flow?
32. In general, the additional oil recovery from a fractured reservoir requires additional pore volumes even for a conventional water flooding. In this context, how many additional pore volumes may be required for a low salinity effect to take into place as it involves the stripping of cat-ions resulting from ion exchange? If so, what would the additional pore volumes required would depend on?
33. Will it be feasible to consider the conventional LSWF mechanisms such as (a) migration of fine particles; (b) pH effect; (c) Multiple-Ion-Exchange (MIE) effect; (d) Expansion of double-layer phenomena; (e) Dispersion at the pore-scale; (f) Dissolution of rock-minerals; (g) Viscosity and Inter-Facial-Tension (IFT) variation and (h) Osmosis – both within the low-permeable rock-matrix as well as within the high-permeable fracture? In addition, will it be feasible to quantify the contribution from each of the above mechanisms towards altering the wettability from an initially more oil-wet state to a more water-wet state in both fracture and rock-matrix?
34. Can we expect a significant change in Capillary Number upon the injection of low saline brine? How exactly the behaviour of capillary desaturation profiles for a fractured reservoir (at constant wettability) will be differing from that of a conventional sandstone reservoir?
35. Will the approach of moving towards more water-wet from more mixed-wet and more oil-wet would really reduce the trapped residual oil in a fractured reservoir upon the injection of low saline brine?
36. Will it be feasible for the capillary waves (resulting from snap-off phenomena) to establish the continuity of fluid fluxes at the fracture-matrix interface? Or the fracture-matrix interface will tend to distort the connected pathways and eventually would lead to the formation of an individual oil ganglia?
37. Due to the extreme variations in permeability between fracture and rock-matrix, will the interfacial forces and viscous forces associated with the oil-brine displacement act over varying length-scales? Whether the spatial and temporal scales of a Haines jump deserve a special attention in the context of a low saline effect in a fractured reservoir?
38. How precisely the problem such as low salinity water injection that is associated with a multiple length- and time-scale can be efficiently used in a fractured reservoir in order to deduce the optimal composition of the injected brine?

39. What will be the threshold enhancement in pressure drop required for the additional oil recovery upon the injection of low saline brine in a fractured reservoir? To what extent the reservoir temperature; the injected composition of the saline brine; and the initial water saturation would influence the increment in pressure drop associated with the wettability alteration?
40. What will be the optimal composition of the injected saline brine that would initiate the recovery of oil at a higher water-cut?
41. How does the low salinity effect associated with the injection of low saline brine in a fractured reservoir differ from that of an alkaline flooding?
42. The transition from more mixed-wet and oil-wet to more water-wet upon the injection of low saline brine require the presence of clay minerals associated with an elevated reservoir temperature for a fractured carbonate reservoir?
43. The transition from more mixed-wet and oil-wet to more water-wet upon the injection of low saline brine require the presence of more divalent cat-ions (such as Calcium, Magnesium and Sulphate ions) also in addition to the injection of low saline brine in a fractured carbonate reservoir?
44. What will be the most decisive factor in reducing the adhesive forces upon the injection of low saline brine in a coupled fracture-matrix system? Will it be the expansion of double layer or the multiple ion exchange mechanism?
45. Will it be feasible to have a low salinity effect in the absence of reversal of wettability in a fractured reservoir?
46. To what extent, the reservoir geology (sandstone or carbonate reservoirs) would influence the resulting low-salinity effect in a fractured reservoir?
47. To what extent, the fracture-parameters (fracture length, fracture width, fracture spacing, fluid velocity within the fracture) as well as the rock-matrix parameters (matrix diffusion coefficient, matrix porosity and matrix tortuosity) will dictate the resulting low salinity effect in a fractured reservoir?
48. To what extent, the macro-dispersion resulting from the differential advection (having very high fluid velocity within the high-permeable fracture and a near-zero or very low fluid velocity within the rock-matrix) will influence the low salinity effect associated with a fractured reservoir?
49. On top of controlling the salinity of the injected brine outside the reservoir, whether the diffusive fluid mass transfer at the fracture-matrix interface would really alter the resultant salinity of the injected brine?

5. Conclusions

An attempt has been made in order to deduce the possible conceptual model associated with a fractured reservoir using the dual-porosity approach for implementing the LSWF technique. Since, a fractured reservoir is characterized by multi-continuum concept as against the conventional single-continuum concept based LSWF in sandstone reservoirs, the various complexities associated with a fractured reservoir during the LSWF has been listed in detail. The following conclusions have been drawn from this study.

1) Low salinity water flooding technique requires a lot of experimental investigations before venturing into field-scale studies in order to consider this as a potential EOR technique in a fractured reservoir.
2) The dominant physical and chemical processes associated with the injection of low saline brine needs to be deduced explicitly for high-permeable fracture and low-permeable rock-matrix.
3) Considering the effect of low-salinity only within the rock-matrix seems to be more meaningful rather than considering the effect simultaneously in both fracture and rock-matrix.
4) Deducing the injection rate of low saline brine as a function of fracture and rock-matrix parameters has the potential to be a "game changer" in fractured reservoirs.
5) Out of the two proposed models, Model 1, where the recovery of the additional oil resulting from the low salinity effect associated with the low-permeable rock-matrix only –

seems more realistic, rather than Model 2, where the contribution of additional oil results from both fracture and rock-matrix.

6) The injection of low saline brine will be a strong function of fracture-parameters (fracture length, fracture width, fracture spacing, fluid velocity within the fracture) as well as the rock-matrix parameters (matrix diffusion coefficient, matrix porosity and matrix tortuosity).

The authors strongly believe that these discussions will provide more insights to further investigate LSWF in a complex fractured reservoir.

References

[1] Sharma T, Kumar GS, and Sangwai, JS. Enhanced oil recovery using oil-in-water (o/w) emulsion stabilized by nanoparticle, surfactant and polymer in the presence of NaCl. Geosystem Engineering, 2014; 17(3): 195-205.

[2] Sharma T, Kumar GS, and Sangwai, JS. Viscosity of the Oil-in-Water Pickering Emulsion Stabilized by Surfactant-Polymer and Nanoparticle-Surfactant-Polymer System. Korea-Australia Rheology Journal, 2014; 26(4): 1-11.

[3] Sharma T, Kumar GS, and Sangwai JS. Viscoelastic properties of oil-in-water (o/w) Pickering emulsion stabilized by surfactant–polymer and nanoparticle–surfactant–polymer systems. Industrial & Engineering Chemistry Research, 2015; 54(5): 1576-1584.

[4] Sharma T, Kumar GS, Chon BH, and Sangwai, JS. Thermal stability of oil-in-water Pickering emulsion in the presence of nanoparticle, surfactant, and polymer. Journal of Industrial and Engineering Chemistry, 2015; 22: 324-334.

[5] Sharma T, Kumar GS, and Sangwai JS. Comparative effectiveness of production performance of Pickering emulsion stabilized by nanoparticle–surfactant–polymerover surfactant–polymer (SP) flooding for enhanced oil recoveryfor Brownfield reservoir. Journal of Petroleum Science and Engineering, 2015; 129: 221-232.

[6] Sivasankar P, and Kumar GS. Numerical modelling of enhanced oil recovery by microbial flooding under non-isothermal conditions. Journal of Petroleum Science and Engineering, 2014; 124: 161-172.

[7] Sivasankar P, and Kumar GS. Improved empirical relations for estimating original oil in place recovered during microbial enhanced oil recovery under varied salinity conditions. Petroleum Science and Technology, 2017; 35(21): 2036-2043.

[8] Sivasankar P, and Kumar GS. Influence of pH on dynamics of microbial enhanced oil recovery processes using biosurfactant producing Pseudomonas putida: Mathematical modelling and numerical simulation. Bioresource technology, 2017; 224: 498-508.

[9] Sivasankar P, and Kumar GS. Modelling the influence of interaction between injection and formation brine salinities on in-situ microbial enhanced oil recovery processes by coupling of multiple-ion exchange transport model with multiphase fluid flow and multi-species reactive transport models. Journal of Petroleum Science and Engineering, 2018; 163: 435-452.

[10] Sivasankar P, and Kumar GS. Influence of bio-clogging induced formation damage on performance of microbial enhanced oil recovery processes. Fuel, 2019; 236: 100-109.

[11] Srinivasareddy D, and Kumar GS. A numerical study on phase behavior effects in enhanced oil recovery by in situ combustion. Petroleum Science and Technology, 2015; 33(3): 353-362.

[12] Srinivasa Reddy D, and Kumar GS. Numerical Simulation of Heavy Crude Oil Combustion in Porous Combustion Tube. Combustion Science and Technology, 2015; 187(12): 1905-1921.

[13] Abhishek R, Kumar GS, and Sapru RK. Wettability alteration in carbonate reservoirs using nanofluids. Petroleum Science and Technology, 2015; 33(7): 794-801.

[14] Sivasankar P, Kanna AR, Kumar GS, and Gummadi SN. Numerical modelling of biophysicochemical effects on multispecies reactive transport in porous media involving Pseudomonas putida for potential microbial enhanced oil recovery application. Bioresource Technology, 2016; 211: 348-359.

[15] Kumar GS, and Reddy DS. Numerical modelling of forward in-situ combustion process in heavy oil reservoirs. International Journal of Oil, Gas and Coal Technology, 2017; 16(1): 43-58.

[16] Berg S, Cense AW, Jansen E, and Bakker K. Direct experimental evidence of wettability modification by low salinity. Petrophysics, 2010; 51(05).

[17] Yousef AA, Al-Saleh SH, Al-Kaabi A, and Al-Jawfi MS. Laboratory investigation of the impact of injection-water salinity and ionic content on oil recovery from carbonate reservoirs. SPE Reservoir Evaluation & Engineering, 2011; 14(05): 578-593.
[18] Hadia NJ, Hansen T, Tweheyo MT, and Torsæter O. Influence of crude oil components on recovery by high and low salinity waterflooding. Energy & Fuels, 2012; 26(7): 4328-4335.
[19] Hadia NJ, Ashraf A, Tweheyo MT, and Torsæter O. Laboratory investigation on effects of initial wettabilities on performance of low salinity waterflooding. Journal of Petroleum Science and Engineering, 2013; 105: 18-25.
[20] Spagnuolo M, Callegaro C, Masserano F, Nobili M, Sabatino R, and Blunt MJ. Single-well Chemical-tracer Modeling of Low-salinity-water Injection in Carbonates. Paper SPE-179626-MS presented at SPE Improved Oil Recovery Conference, Tulsa, Oklahoma,USA, 11–13 April 2016.
[21] Amirian T, Haghighi M, and Mostaghimi P. Pore scale visualization of low salinity water flooding as an enhanced oil recovery method. Energy Fuels, 2017; 31(12):13133–13143.
[22] Islam MS, Kleppe J, Rahman MM, and Abbasi F. (2018, August). An Evaluation of IOR Potential for the Norne Field's E-Segment Using Low Salinity Water-Flooding: A Case Study. Paper SPE-192418-MS presented at SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition. Dammam, Saudi Arabia, 23–26 April 2018.
[23] Bartels WB, Mahani H, Berg S, and Hassanizadeh SM. Literature review of low salinity waterflooding from a length and time scale perspective. Fuel, 2019;236: 338-353.
[24] Han P, Geng J, Ding H, Zhang Y, and Bai B. Experimental study on the synergistic effect of nanogel and low salinity water on enhanced oil recovery for carbonate reservoirs. Fuel, 2020; 265: 116971.
[25] Martin JC. The effects of clay on the displacement of heavy oil by water. Paper SPE 1411-G presented at the Venezuelan Annual Meeting. Caracas, Venezuela, 14–16 October 1959.
[26] Bernard GG. Effect of floodwater salinity on recovery of oil from cores containing clays. Paper SPE 1725 presented at the SPE California Regional Meeting. Los Angeles, CA, 26–27 October, 1967.
[27] Tang GQ, and Morrow NR. Influence of brine composition and fines migration on crude oil/brine/rock interactions and oil recovery. Journal of Petroleum Science and Engineering, 1999; 24(2-4): 99-111.
[28] McGuire PL, and Chatham Jr, 2005. Low salinity oil recovery: An exciting new eor opportunity for Alaska’s North slope. Paper SPE 93903 presented at the Western Regional Meeting. Irvine, 30 March–1 April 2005.
[29] Lager A, Webb KJ, Black CJJ, Singleton M, and Sorbie KS. Low salinity oil recovery-an experimental investigation1. Petrophysics, 2008; 49(01).
[30] Kumar GS, and Ghassemi A. Numerical Modeling of Non-Isothermal Quartz Dissolution/Precipitation in a Coupled Fracture-Matrix System. Geothermics, 2005; 34(4):411-439.
[31] Kumar GS, and Sekhar M. Spatial Moment Analysis for Transport of Nonreactive Solutes in a Fracture-Matrix System. Journal of Hydrologic Engineering, 2005; 10(3): 192-199.
[32] Kumar GS, Sekhar M. and Misra D. Time Dependent Dispersivity Behavior of Non-Reac-tive Solutes in a System of Parallel Fractures. Hydrology and Earth System Sciences Discus-sions, 2006; 3(3): 895-923.
[33] Sekhar M, and Kumar GS. Modeling Transport of Linearly Sorbing Solutes in a Single Fracture: Asymptotic Behavior of Solute Velocity and Dispersivity. Geotechnical and Geological Engineering, 2006; 24(1) :183-201.
[34] Kumar GS, and Ghassemi A. Spatial Moment Analysis for One-Dimensional Nonisothermal Quartz Transport and Dissolution/Precipitation in a Fracture-Matrix System. Journal of Hydrologic Engineering, 2006; 11(4): 338-346.
[35] Sekhar M., Kumar GS, and Mishra D. Numerical Modeling and Analysis of Solute Velocity and Macrodispersion for Linearly and Nonlinearly Sorbing Solutes in a Single Fracture with Matrix Diffusion. Journal of Hydrologic Engineering, 2006; 11(4): 319-328.
[36] Ghassemi A, and Kumar GS. Changes in fracture aperture and fluid pressure due to thermal stress and silica dissolution/precipitation induced by heat extraction from subsurface rocks. Geothermics, 2007; 36(2): 115-140.
[37] Kumar GS. Effect of Sorption Intensities on Dispersivity and Macro-dispersion Coefficient in a Single Fracture with Matrix Diffusion. Hydrogeology Journal, 2008; 16(2): 235-249.
[38] Kumar GS. Influence of Sorption Intensity on Solute Mobility in a Fractured Formation. Journal of Environmental Engineering, 2009; 135(1): 1-7.

[39] Kumar GS. Mathematical Modeling on Transport of Petroleum Hydrocarbons in Saturated Fractured Rocks. Sadhana – Academy proceedings in Engineering Sciences, 2014; 39(5): 1119-1139.
[40] Kumar GS. Mathematical Modeling of Groundwater Flow and Solute Transport in a Saturated Fractured Rock using Dual-Porosity Approach. Journal of Hydrologic Engineering. 2014; 19(12): 04014033-1 – 04014033-8.
[41] Kumar GS. Subsurface transport of nuclear wastes in the Indian subcontinent. ISH Journal of Hydraulic Engineering, 2015; 21(2): 162-176.
[42] Kumar GS. Modeling Fluid Flow through Fractured Reservoirs: Is it different from Conventional Classical Porous Medium? Current Science, 2016;110(4):695-701.
[43] Kumar GS, M. Sekhar and D Mishra. Time dependent dispersivity of linearly sorbing solutes in a single fracture with matrix diffusion. Journal of Hydrologic Engineering, 2008; 13(4): 250-257.
[44] Natarajan N, and Kumar GS. Radionuclide and colloid co transport in a coupled fracture-skin-matrix system. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2010; 370(1-3): 49-57.
[45] Natarajan N, and Kumar GS. Numerical Modeling and Spatial Moment Analysis of Thermal Fronts in a Coupled Fracture-Skin-Matrix System. Geotechnical and Geological Engineering. 2011; 29(4): 477-491.
[46] Natarajan N, and Kumar GS. Evolution of fracture permeability due to co-colloidal bacterial transport in a coupled fracture-skin-matrix system. Geoscience Frontiers. 2012; 3(4): 503-514.
[47] Natarajan N, and Kumar GS. Lower order spatial moments for colloidal transport in a fracture-matrix coupled system. ISH Journal of Hydraulic Engineering, 2014;20(2):200-211.
[48] Natarajan N, and Kumar GS. Numerical Modeling and Spatial Moment Analysis of Solute Transport with Langmuir Sorption in a Fracture Matrix Coupled System. ISH Journal of Hydraulic Engineering, 2015;21(1):28-41.
[49] Renu V, and Kumar GS. Numerical Modeling and Spatial Moment Analysis of Solute Mobility and Spreading in a Coupled Fracture-Skin-Matrix System. Geotechnical and Geological Engineering, 2012;30(6):1289-1302.
[50] Renu V, and Kumar GS. Temporal Moment Analysis of Solute Transport in a Coupled Fracture-Skin-Matrix System. Sadhana – Academy proceedings in Engineering Sciences, 2014;39(2):487-509.
[51] Renu V, and Kumar GS. Temporal moment analysis of multi-species radionuclide transport in a coupled fracture-skin-matrix system with a variable fracture aperture. Environmental Modeling & Assessment, 2016; 21(4): 547-562.
[52] Renu V, and Kumar GS. Numerical Modeling on Benzene Dissolution into Groundwater and Transport of Dissolved Benzene in a Saturated Fracture-Matrix System, Environmental Processes, 2016; 3(4): 781-802.
[53] Renu V, and Kumar GS. Multi-component transport of BTX in a discretely fractured aquifer with fracture–skin: numerical investigation and sensitivity analysis. Environmental Earth Sciences, 2017; 76(17): 619.
[54] Renu V, and Kumar GS. Multispecies Transport Modeling on Biodegradation of BTX in a Saturated Fracture-Matrix System with Multiple Electron Acceptors". Environmental Engineering Science. Environmental Engineering Science, 2018; 35(10), 1096-1108.
[55] Renu V, and Kumar GS. (2018). "Mathematical Modeling on Mobility and Spreading of BTEX in a Discretely Fractured Aquifer System under the Coupled Effect of Dissolution, Sorption, and Biodegradation". Transport in Porous Media (Springer Publications), 2018; 123(2): 421-452.
[56] Bagalkot N, and Kumar GS. Thermal front propagation in variable aperture fracture–matrix system: A numerical study. Sadhana, 2015; 40(2): 605-622.
[57] Bagalkot N, and Kumar GS. Effect of nonlinear sorption on multispecies radionuclide transport in a coupled fracture-matrix system with variable fracture aperture: a numerical study. ISH Journal of Hydraulic Engineering, 2015; 21(3): 242-254.
[58] Bagalkot N, and Kumar GS. Effect of random fracture aperture on the transport of colloids in a coupled fracture-matrix system. Geosciences Journal, 2017; 21(1): 55-69.
[59] Bagalkot N, Zare A, and Kumar, GS. Influence of fracture heterogeneity using linear congruential generator (lcg) on the thermal front propagation in a single geothermal fracture-rock matrix system. Energies, 2018; 11(4): 916.

[60] Bagalkot N, and Kumar GS. Colloid transport in a single fracture–matrix system: Gravity effects, influence of colloid size and density. Water, 2018; 10(11): 1531.

[61] Kumar GS, and Rakesh TV. Numerical modeling of reactive solute transport in a single fracture with matrix diffusion under complex boundary condition. ISH Journal of Hydraulic Engineering, 2015;21(2): 125-141.

[62] Kumar GS, and Rakesh TV. Numerical modeling of hyperbolic dominant transient fluid flow in saturated fractured rocks using Darcian approach. Groundwater for Sustainable Development, 2018; 7: 56-72.

[63] Gudala M, and Kumar GS. Numerical modelling of coupled single-phase fluid flow and geomechanics in a fractured porous media. Journal of Petroleum Science and Engineering, 2020; 191: 107215.

[64] Kumar A, and Kumar GS. Numerical investigations on compressible non-linear fluid flow associated with a stress-sensitive fractured reservoir. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2020; 1-20.

[65] Kumar GS, Mishra A, and Kumar A. Darcy- and Pore-Scale Issues associated with Multi-phase Fluid Flow through a Petroleum Reservoir. Earth Sciences Malaysia, 2020; 4(2): 93-102.

[66] Brady PV, Morrow NR, Fogden A, Deniz V, and Loahardjo N. Electrostatics and the low salinity effect in sandstone reservoirs. Energy & Fuels, 2015; 29(2): 666-677.

[67] Jha NK, Iglauer S, Barifcani A, Sarmadivaleh M, and Sangwai JS. Low-salinity surfactant nanofluid formulations for wettability alteration of sandstone: role of the SiO2 nanoparticle concentration and divalent cation/SO42–ratio. Energy & Fuels, 2019; 33(2): 739-746.

[68] Kakati A, Jha NK, Kumar G, and Sangwai JS. Application of low salinity water flooding for light paraffinic crude oil reservoir. Paper SPE-189249-MS presented at SPE Symposium: Production Enhancement and Cost Optimisation, Kuala Lumpur, Malaysia, 7-8 November 2017.

[69] Morrow N, and Buckley J. Improved oil recovery by low-salinity waterflooding. Journal of Petroleum Technology, 2011; 63(05): 106-112.

[70] Katende A, and Sagala F. A critical review of low salinity water flooding: Mechanism, laboratory and field application. Journal of Molecular Liquids, 2019; 278: 627-649.

To whom correspondence should be addressed: professor Suresh Kumar Govindarajan, Reservoir Simulation Laboratory, Petroleum Engineering Programme, Department of Ocean Engineering, Indian Institute of Technology – Madras, Chennai, India, E-mail: gskumar@iitm.ac.in