A REVIEW STUDY ON MICRO-FLUID CHIPS FOR ENHANCING THE OIL RECOVERY BY INJECTING THE CHEMICAL FLOODS

by

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Surfactant and polymer flooding are the vital techniques used in petroleum industry to enhance the oil recovery. Development and advancement in such techniques has occurred time by time to overcome the challenges of oil and gas recovery. However, micro-fluid chips and its development provide a new way to understand the real time behavior of fluid-flow in porous media. The essence of this study has been achieved by collecting the information from literature studies and sorted the useful information organize the pattern of micromodels chip revolution. In this study, first precise review is conducted by the innovations of micromodel chips into timescale from 1952 till date. Second, advancement in micromodel chip technology is included based on different periods of time where micromodel chips have evolved from chip design to nanoscale visualization of chips. Third, some recommendations are proposed based on evolution of micromodel chip technology that it not only requires less time but also minimizing the massive experimental set-up and complications. The overall finding of this research propose that in current times some micro-fluidic reforms made recently has played versatile role in improving injection chemical selection and similar improvements are expected to be developed in near future.

Key words: *chemical flooding, micro-fluidic chips, enhanced oil recovery, fluid displacement, fluid visualization*

Introduction

In enhanced oil recovery especially at pore scale level during oil displacement in permeable medium the analysis of micro-fluidic delivers a brilliant break through to describe the displacement mechanism broadly. In recent years, application in science and engineering field have improved the models with realistic geological pore geometries and also exerted the higher pressure as well [1]. Moreover, industries and academia have widely used micro-fluidic because of the many reasons such as it not only shortens the experimental time but also reduces reagent volumes and save the costs as well. Basically, micro-fluidics is a technical field of study which shows flow passage, flow control and manipulation of liquid substances from large to small volume *i. e.* micro to nano, micro or macro. It has been broadly used to understand the basic flow behavior in permeable medium for example single phase flow of Newtonian [2] and non-Newtonian [3] fluids, multi-phase flow, cross interface mass-transport and [4] mechanisms

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of droplet formation [5] coalescence [6]. Also, it is used to assess the polymer effectiveness especially when dealing with pore-scale phenomena due to its advantages such as it is low cost and frequently more illustrative of the medium than modelling. Micromodel is an etched flow pattern which can be viewed with a microscope. It has been implemented to investigate different multi-phase flow phenomena in porous media at the pore level. Due to some recent advancement in micromodel chips, such as design of single-channel patterns with variable cross-section size, it provides opportunity to study the emulsion flow in parallel conduits [7], trapping of non-wetting phase at pore-throat structures and geometries pertinent to enhanced oil recovery [8] and the research in reservoir engineering. Additionally, 2-D and 3-D features in the micromodel geometry has been developed and commonly used but both have some limitations. For example, in 2-D, the snap-off feature cannot be accurately investigated because the channel's depth in micromodel is uniform [9], concern attached to investigate a narrow range of permeable mediums but it can be minimized using stochastic modelling [10], *etc.* while in (3-D), physics is required in porous media especially for multi-phase flow where capillary effects are prominent, resolution and material limit, and 3-D printing technology [11]. Unfortunately, these limitations make it unmanageable to construct a 3-D micromodel as a basic model of truly micron-scale permeable medium [7, 12].

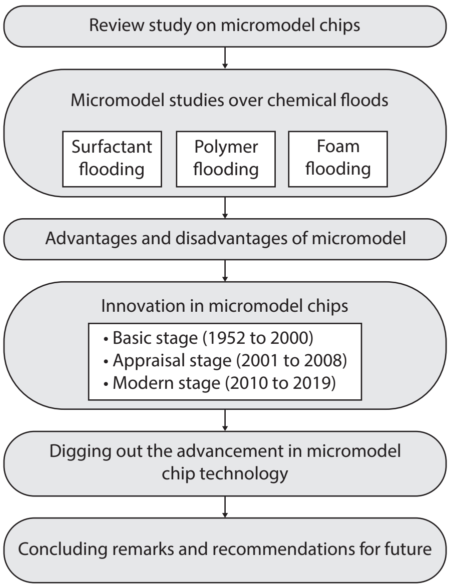

Figure 1. A systemic diagram of methodology used in this study

The microchips aid to acquire real-time flow behavior and appropriate in-situ phenomena by visualizing the fluid-flow [9] and it may provide opportunity to enhanced oil recovery. It also includes the regularizing and processing of the small liquid volumes which enhances the performances at low cost. The graphical curve of the fluid-flow path can be taped on computer via using camera and microscope and results providing the fascinating feature like fluids react at micro scale. Based on the literature, the main objectives of this study are: to review the essential of micromodel chips and its development by employing the chemical floods for enhancing the oil recovery and to discuss the development of micro model chips with the passage of time.

The methodology followed to conduct this study is described fig. 1. The data have been collected from various studies and analyzed first and then discussed the challenges of micromodel chips and its development with the passage of time. At the end, the recommendations have been given for further development on micromodel chips.

Micromodel control and visualization

Fluid injection system and pressure transducers

Syringe pumps like Teledyne Isco Model 100 DM [13] analytical syringe pump, Nexus 3000 KR [14]. Reservoirs for surfactants, crude-oil and surfactants and vessels for gas, brine solution are used in fluid injection system. The rate of injection differs from microliter per minute to milliliter per minute. Tubing, connectors and ferrules form the accessories of this system. In order to quantify the differences in pressure as well as absolute pressure at a point, pressure transducers were used. Pressure difference between inlet and outlet ports were measured by connecting the pressure tube [15]. Pressure is measured in bar. System comprising a transducer, digital interface box and display on computer screen.

Micromodel holder and temperature control

Micromodel was placed in a holder, which has conduits. Tubes from pumps were attached to micromodels chips via these conduits. Holder consisting of two inlet and two outlet ports could be coated with aluminum. Ports of holder are aligned with micromodel ports. Ports are then sealed with O-rings [13, 15]. By placing the assembled chip and holder at hot plate, the experiments can be performed at desired temperature.

Optical system and image analysis

An optical system comprising of microscope, eternal light source, camera and imaging software was used by [14]. A normal, a refraction microscope Accu-Scope EXI-310 [16] or Nikon Eclipse TI-FL inverted microscope can be used. Micromodel was placed above objective lense, range of objective lenses 2×, 10, and 20× are used for zooming in or out. Nikkon intense light used as external light source to deliver it to microscope.

The images get by optical system was interpreted by using Software such as Texas, LabView 2011 National Instruments, MATLAB Conn [17], Nikon NIS Elements imaging software [14] and GIMP open source imaging software [17] and ImageJ [16] can be used.

Coloring, detection of chemicals and cleaning system

Florescence filters could be added to the microscope with each filter giving different wavelength of light. Proper selection was done in case fluids and florescent additives. Fluorescein, FT175 was used as an additive in case of distilled water, for Decane Nile red was used. Nile red has great solubility in hydrophobic lipids and organic solvents but insoluble in water, used by [14]. Hence in micromodels, it was a good dye to distinguish the between fluids-flow.

In comparison core, a micromodel can be used for many times. A cleaning system was utilized for cleaning of fresh micromodel, to make it ready for chemical flooding experiment as required wettability and also it's cleaning after usage. The formed precipitates of chemicals can block the pores by clogging in them. So a gradual process is used for cleaning. Isopropanol is pushed with the help of water into the micromodels and holders to remove remaining oil. The process is repeated unless until only immobile oil is left in the micromodels. Toluene is then used to remove remaining oil. Process is repeated till there is no visible oil left or only few immobile patches were there. Then to remove toluene CO_2 is pumped [13] .In order to keep water, wet or oil wet conditions of micromodels certain procedures were used and followed. To maintain water wet situationluene, vacuum, distilled water, acetone and hydrochloric acid were used and to maintain oil wet situation dehydrated toluene, sodium hydroxide, methanol and trichloro-methyl silane (TCMS) were used as applied by [18].

Micromodels studies for enhanced oil recovery by injecting different chemical floods

Surfactant flooding

The surfactant and water flooding are the techniques which are usually used in the industries to enhance the oil recovery. A trapped residual oil has produced after water flooding with surfactant solutions through this technique. Basically, this technique lowers the interfacial tension between the phases present in the reservoir and resulted enhance the oil recovery. Many studies in literature has focused on mechanisms and behavior of surfactant flooding, however combined impact of surfactant with another agent have not been well understood yet. Jamaloei, and Kharrat [19] studies deliver a new vision of surfactant flooding using micromodel by considering the effect of wettability on displacement mechanisms of microscopic two-phase flow. The pore-network geometry of the micromodel was first drafted using Freehand Graphics and CorelDraw Graphics and then printed on the paper. Duplication was done on glass by using etch technique and finally fusing of the pore-network patterns were done to construct a homogenous etched depth. It was inferred from experimental results that in oil wet medium the ultimate oil recovery values of water flooding and dilute surfactant flooding were lower than those in water-wet medium.

Hematpour *et al*. [20] have studied both quantitatively and qualitatively investigation of the surfactant flooding behavior in low viscosity oil considering the quarter five-spot glass micromodel and studied the effects of different parameters on oil recovery. The width and length of the float plate and cover plate was same *i. e.*, 10.14 cm and 17.78 cm, respectively. The radius of the inlet and outlet port was 1.5 mm. In this glass micromodel, the pore-network pattern was etched on float plate having nominal 5 mm thickness. Fusing technique was used to seal the etched and cover plate. Thus, an enclosed pore space was formed. The experimental results showed that hike in surfactant concentration led to greater recovery as compared to water flooding in low viscosity oil while increase in co-surfactant concentration, ultimate recovery goes down.

Polymer flooding

The polymer flood is one of the most versatile EOR technique wherein polymer is injected into the reservoir for alteration the physical properties of fluids and resulted enhance the oil recovery. Micromodels have been practiced in order to understand the behavior of polymer such effect of temperature, viscosity, salinity and pore geometry on it. Following studies have been done regarding polymer flooding. For example, Emami Meybodi *et al.*, [21] studied the effect of wettability on microscopic mechanisms as well as macroscopic behavior of polymer flooding by employing a one quarter five-spot 2-D glass micromodel. The dimension of the pore network was 60 mm × 60 mm with aspect ratio 2.33. The porosity and permeability of the homogenous designed micromodel was 28.6 ± 0.05 and 1.33 ± 0.09. Hydrofluoric acid was used for etching the pattern on glass plate and fusing was done by putting the covered plate on it, thus enclosed pore space was created. The covered plate has an inlet and outlet which used to move the fluids throughout the pore network. The results drawn from this study revealed that in water-wet medium, frequent sweep of the oil phase at pore to pore network and discontinuity of polymer solution with in the pore necks whereas in oil wet medium, a trapped water phase was experienced within the oil. Moreover, it showed that a polymer higher concentration, degree of hydrolysis and molecular weight results found in polymer solution that was a lower oil-polymer viscosity ratio and higher apparent viscosity. Both water and oil wet medium produced favorable microscopic displacement mechanism to enhanced sweep efficiency. Rock *et al.* [22] used Glass-Silicon-Glass micromodel resembling permeable medium to study the advanced flow behavior characterization of viscoelastic polymer solutions used in enhanced oil recovery demonstration. The permeability and porosity of the micromodel was approximately 3-4 D and 33.25% while the calculated mean grain radius was 36.5-41 μm. The dimension of the micromodel was 40 mm × 40 mm × 0.05 mm. The porous structure was etched into silicon which is medium layer covered by glass layer on the top and bottom. The experimental results conclude that:

– apparent viscosity increase with increasing polymer concentration and molecular weight and also increase with decreasing solvent salinity,

- the onset of shear thickening and shear rate of elastic turbulence decrease with decreasing salinity, increasing molecular weight and increasing concentration, and
- a dissimilar correlation between the onset of shear thickening and elastic flow instability was found. Since elastic turbulence flow was believed to contribute in oil recovery enhancement and provides better understanding of flow behavior characterization.

Advantages and disadvantages of the micromodels

The advantages and disadvantages of various micromodels are shown in tab. 1.

Table 1. Advantages and disadvantages of the micromodel

Model	Advantage	Disadvantage
Glass bead monolayers [23]	This technique allows the use of very large saples (diameter~1 m) without requiring any specific pattern of the porous medium	The difference of wettability between the glass beads and the plastic sheet can be a problem for oil/water displacements
Glass micromodels [24]	In it pore of lenticular shape, 50-100 μm deep and channels at a distance of about 1 mm The reproduction of any network pattern made from a photograph or generated by computer Non-planarity has significant quantitative effects on trapped saturations and relative permeabilities	Non-planarity has small qualitative effect on the displacement mechanisms
PDMS micromodels [25]	PDMS micromodels work effectively at room temperature	Organic solvent usage cause swelling of polymer as these solvents was not compatible with PDMS
Resin micromodels [26]	It is the well-controlled shape of the channels allowing the direct comparison of experiments with computer simulations: a rectangular cross-section with a constant depth of 1mm and a minimum width of 0.2 mm	The main drawback of resin is the wettability hysteresis when oil and water are used together

Quest for solution in innovation of micromodels chip

The concept of chemical injection agents for enhancing the oil recovery started from 1952 and improvement in chemical injection has been occurred time by time with the growth of technology. After that the level of improvement was extended to entirely innovations and today the trend of technology has totally different and modern concept, thus this whole journey of improvement has been described in following stages.

Stage-I (1952 to 2000)

The long lasting stage with almost five decades of study period showed that the main focus of all the studies was centered to improve the oil recovery technique by using different chemical agents. This stage comprised of advancement on initial methods that were proposed to enhance the oil recovery from technically challenged reservoirs. From 1988 the technique of microbial enhanced oil recovery was also under consideration of many researchers. The researchers also adopted the visualization techniques as this technique provides the overall description of the physical shape of the reservoir after certain chemical agent is injected. Right after the visualization goes main stream the testing of emulsions was also an easier task hence most of the studies declined to observe the effect of emulsions in reservoir. Empirical methods were not sufficient to prove the recovery improvement from reservoir therefore, mix of multiple techniques was also adopted by various scientists in this stage.

Stage-II (2001 to 2008)

The stage extended to only decade showed more progress as compared to previous stage. Because by the time this stage of technology was approached the scientist became mature enough to figure out that in order to improve the oil recovery the role of oil is not only factor but the reservoir rock properties also play the equal part in producing the oil from subsurface. Hence, multifunctional chemical injection was adopted and therefore, this stage can be distinguished from previous stage. In this stage, researchers were more focused on discussing the role of wettability and pore geometry, in fact in 2007, 2008 numerous innovations were proposed which were based on petrophyscial rock behavior. Also microscopic displacement was a main focus in this stage. By time researcher were focused to improve the chemicals they also used lab scale models that can help to understand the new horizons of reservoir and can make difference in enhancing the oil recovery. Pore network models and porous media were also improved in this stage. The major achievement of this stage was adaptation of different kinds of injection agents based on type and nature of reservoir rock and fluid, that are selection of polymer, alkaline or surfactant was also revolutionized which rose the stacks of oil production process.

Stage-III (2010 to 2019)

The stages which last even less than a decade have showed most remarkable discoveries and innovations. As by the time science of enhanced oil recovery entered this stage the style of engineering has also changed. As in this stage researcher were inclined to use computational technique which was mix of empirical, chemical and enhanced oil recovery techniques. In this stage, the notable achievement was usage of dual porosity concept which was highly popular in 2012 among researchers. Further, dual porosity models were improved by visualization technique. The rheological advancements proposed in this sage also hold a big innovation with respect to change in oil supply and demand phases. Highly viscous oils can now also be displaced as strong viscosity altering agents has been introduced. Adaptation of nanoparticle technology changed the whole process of enhancing the oil recovery because recent improvements in chemical injection agents have provided very effective solutions to oil displacement problems. Utilization of fractures for enhancing the oil recovery is also possible now as various researches have been presented in this domain as well. Above all the recent development of micromodel chips has revolutionized the whole enhanced oil recovery science. Now the extreme challenges can also not only be visualized but also solved at lab scale with less financial involvement. Further, the proposed solutions can be taken to industry for pilot testing or field applications. Hence, the challenges in the field of enhanced oil recovery has keep on expanding but with the time equal intensity of solutions has been proposed. Thus the field of chemical enhanced oil recovery has lager area for improvisation with technological innovations.

Advancements in micromodel chip technology

The design and parameters studied by means of micromodel chip technology has emerged rapidly within last decade and the modern micromodel chip studies have initially focused on chip design [27, 28]. In order to understand the emergence of micromodel chip technology, the technological advancements are classified into time periods. The initial period, appraisal period, development period and future of micromodel chip period. The initial period of such studies was observed before 2013 where parameters for micromodel chip technique were investigated at larger scale. Figure 2 shows some studies published during initial period of micromodel chip technology.

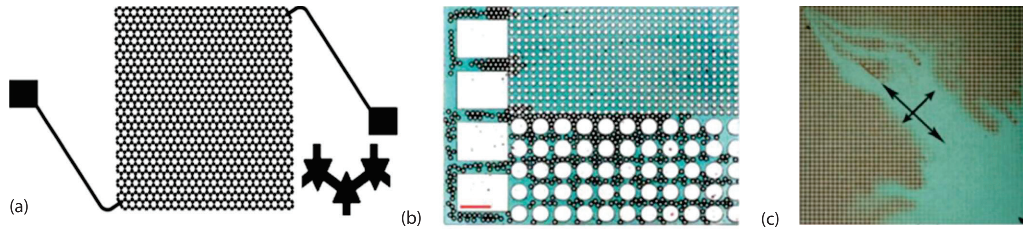

Figure 2. Studies from initial period of micromodel chip technology; (a) schematic of the micromodel and enlarged view [19], (b) micro-fluidic design of the heterogeneous porous micromodel [27], and (c) micro-fluidic heterogeneous model [28]

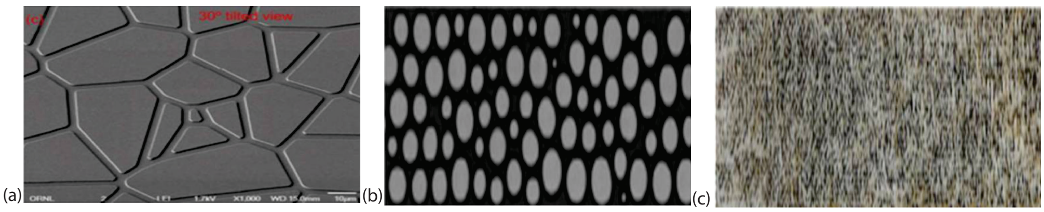

Figure 3. Studies from Appraisal period of micromodel chip technology; (a) electron micrograph of nanofluidic chip [29], (b) bubble formation in pore geometry [30], and (c) pore scale geometry of micro-fluidic chip [31]

The appraisal period started right after 2013 when researchers zoomed in the chips and considered the pore scale geometry of chip design as shown in fig. 3. This advancement enabled engineers and researchers to investigate the rock and fluid interaction in reservoirs during enhanced oil recovery process. Indeed, this period only lasted for two years.

The development period started soon after 2016 when researchers proposed a further expanded zoom into micromodel chip design and dived deep into the fluid mechanics of oil and surfactants in reservoir as shown in fig. 4. This up gradation of study opened a whole new chapter of fluid movement investigation in chips which provided higher efficiencies to understand the dynamic behavior of rock and fluid. However, all the periods of micromodel chip technology according to this study only last for two years.

The future of micromodel chip technology can be seen in fig. 5 where nanoscale visuals of micromodel chip are investigated. Saying it future is somehow not right because things are happening in present but these happening are basically depicting the future era of micromodel chip investigations.

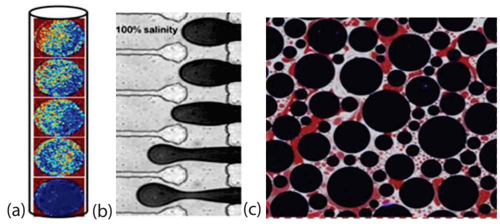

Figure 4. Studies from Development period of micromodel chip technology; (a) residual oil saturation location along the core) [32], (b) schematic of pore-scale snap-off [33], and (c) injection of surfactant and salt solution measure break through time [22]

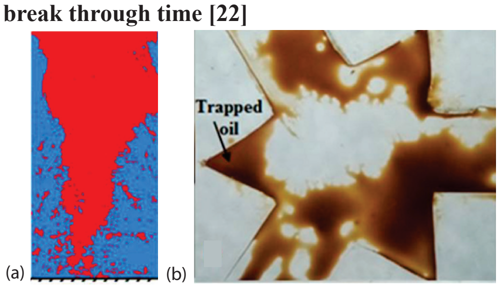

Figure 5. Studies from future of micromodel chip technology; (a) image sequence of oil saturation over time in a fractured micromodel undergoing aqueous surfactant injection [34], (b) digital microscope images of the oil spreading after solution injection in the micromodel showing the pore-scale configuration [35]

Conclusions

Since 1952 to 2019 the three-stages of development in micromodels chip has been described and following conclusion can be drawn from this study:

- The properties like interfacial tension, wettability and fluid viscosity has been the focus of many researchers, however; all the researchers had theoretical approach to the challenges. Because all the proposals required financial and practical resources. Indeed, after the evolution of micromodel chip technology, the approach of research or piloting the project has been changed.
- The micromodel technology has been modified and improvised with respect to time and application requirement. It reduces time as well as space by analyzing through recording the images and videos and other image processing software. Moreover, this technology has revolutionized the conventional experimental set-ups, particularly by reducing the time and location problems.
- Micromodel chip technology for enhanced oil recovery is a novel idea in which work to be done with micromodel chips having pore structures resembling that of various rock samples. Different fluid flows to be carried inside these micromodels which may act as part of displacement mechanisms.
- Using micromodel chip technology, the flow patterns, fingering, front location with respect to time can be studied for different combinations of fluids and pore structures.
- The innovation in micromodel chip has not only supported to improve outcomes of studies or projects but all these factors collectively help to find micro challenges that are accumulated in reservoirs. In fact, now it is quite easier task to procure any proposal for its fitness in field by observing its consequences in experimental labs. Globally, different design and composition of microchips have been developed with different specifications and specialties.
- A common or mono-prescribed chip is sufficient to conduct sensitivity with numerous injection chemicals to observe the effects for optimization. Moreover, the repetition of experiment is never a challenge if reservoir characteristics are known. Furthermore, the experiments can be repeated with different sensitivities.
- The future of micromodel chips in petroleum industry has somehow direct dependency on micromodel chips innovation and its suitability.
- The challenges like core damage, structural modification or core plugging can be discarded rapidly while working with micromodel chips. Notably, such study for enhancing the oil recovery can be extended to rock properties and rock property alteration can also be tested while dealing with micromodel chip technology, because nowaday's various rock or fluid property altering injection chemicals are available.

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