*Iranian Journal of Oil & Gas Science and Technology,* Vol. 2 (2013), No. 3, pp. 48-56
http://ijogst.put.ac.ir

# An Experimental Study of Alkali-surfactant-polymer Flooding through Glass Micromodels Including Dead-end Pores

**M. Esmaeili[1], A. Heydarian[2*], and A. Helalizadeh[1]**

[1] Department of Petroleum Engineering, Petroleum University of Technology, Ahwaz, Iran
[2] Iranian Offshore Oil Company, Tehran, Iran

*Received*: December 27, 2012; *revised*: September 05, 2013; *accepted*: September 10, 2013

## Abstract

Chemical flooding, especially alkaline/surfactant/polymer flooding, is of increasing interest due to the world increasing oil demand. This work shows the aspects of using alkaline/surfactant/polymer as an enhanced oil recovery method in the porous media having a high dead-end pore frequency with various dead-end pore parameters (such as opening, depth, aspect ratio, and orientation). Using glass micromodels makes it possible to manipulate and analyze the pore parameters and watch through the porous media precisely. The results show that polyacrylamide almost always enhances oil production recovery factor (up to 14% in comparison with brine injection) in this kind of porous media. Except at low concentrations of polyacrylamide and sodium carbonate, sodium dodecyl sulfonate improves oil recovery (even 15% in the case of high polyacrylamide concentration and low sodium carbonate concentration). Increasing alkaline concentration reduces recovery factor except at low concentrations of polyacrylamide and high concentrations of surfactant.

**Keywords:** Alkaline/Surfactant/Polymer (ASP), Dead-end Pore, Aspect Ratio, Dead-end Orientation

## 1. Introduction

ASP flooding is still facing some major challenges in produced fluid handling on its way to commercial application. While a significant decrease in water cut of produced fluid and an increase in oil production have been achieved, alkaline (A), surfactant (S), and polymer (P) in produced fluid have resulted in very tight oil-in-water (O/W) emulsion, causing great troubles in surface oil/water separation (Li et al., 2013). The main application of surfactants in enhanced oil recovery is to lower the interfacial tension between an aqueous solution and oil phases. Lowering of interfacial tension recovers additional oil by reducing the capillary forces that leave the oil behind any immiscible displacement. This trapping is best expressed as a competition between viscous forces, which mobilize the oil, and capillary forces, which trap the oil. For this reason, surface-active agents are used to decrease the interfacial tension (IFT) between the oil and water phases (Samanta et al., 2011). Alkali/oil interactions result in the emulsification of the oil. The degree of emulsification depends on the acid number of the oil (Al-Hashim et al., 2005).

The displacement mechanism of an ASP flooding is similar to that of micellar/polymer flooding except that much of the surfactant is replaced by low-cost alkali. Therefore, the overall cost is lower even though the chemical slugs can be larger (Huang and Dong, 2002). ASP flooding pilot can form

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[*] Corresponding Author:
Email: heydarian.put@gmail.com

oil banks, greatly lower water cut, and increase the oil recovery. The incremental oil recovery was about 20% over water flooding. However, a major technical challenge is how to significantly reduce the amount and the cost of chemicals used such that ASP flooding can become cost-effective as well. Field applications show that the concentrations of alkali, surfactant, and polymer remain relatively high in the produced fluids of ASP flooding process. Thus, the successful reuse of these chemicals can substantially reduce the capital cost and the environmental impact (Shutang and Qiang, 2010). While heterogeneity in pore structure is a key concern of researches, it is first necessary to have a clear understanding of the baseline behavior when porosity, permeability, and throat size are tightly controlled. This control was achieved by manufacturing homogenous carbonate-cemented sandstone using the calcite in-situ precipitation system (CIPS). While the recovery of both the refined oil and the crude oil was the same after initial waterflood, the crude oil was mobilized more by the ASP process through both microemulsion and banking processes (Al-Shahri and Liu, 2010).

The main purpose of Tong's study (1998) was to support the coming larger scale test projects; thus some experimental investigations (at 45 °C) were undertaken in glass micromodels (with two kinds of wettability) to study the mechanism of ASP flooding of the residual oil (Daqing waxy crude oil of low acid number) entrapped in porous media.

The capacitance model allows the determination of the amount of dead-end pore space in a porous matrix and the effect of velocity on the rate of diffusion into this space (Coats and Smith, 1964). For the analysis, the total pore space is separated into a main pore structure contributing to the flow through the rock and the dead-end pores serving only for fluid storage (Braun, 1991). The interfacial mass transfer and dead-end pore flooding of $CO_2$ miscibility flooding play an important role in oilfield. This study is mainly conducted by reservoir flow and supercritical fluid theory. Supercritical $CO_2$ miscible flooding mechanism and a special dead-end displacement mechanism are studied (Jishun et al., 2010).

## 2. Experimental set-up

*Micromodel*: understanding of pore-scale transport phenomena can be achieved by microscopic visualization of the porous media. Low-pressure, low-temperature glass micromodels have been used for recovery evaluation and visualization experiments. The patterns required were carved onto a glass surface using laser etching technology with the penetration depth of 0.2 mm. Then, a flat plate was attached to the carved plate by heating up to 780 °C gradually and then was cooled down slowly to ambient temperature to produce a completely sealed glass micromodel (Figure 1). Glass micromodels were generated in the size of $7*11$ $cm^2$ with a porosity of 0.23. The total pore volume of each micromodel was calculated to be about 0.35 cc. Figure 2 shows a schematic of the micromodel set-up.

*Pump*: a high-accuracy, low-rate pump (Quizix QL-700) was used to inject fluids into the micromodels. The injection rate of the pump was in the range of $6\times10^{-4}$ to 10 cc/min.

*Optical System*: a high resolution digital camera (Nikon D-100) was used to take photos from the micromodels. These images were used as the inputs of the analysis system.

*Procedure*: micromodel experiments were based on the recording of the areal efficiency by taking photos at constant time intervals. Before each experiment, the testing glass micromodel was cleaned with the sequential injections of toluene. Then, the glass micromodel was saturated with oil (hydrocarbon fluid). Afterward, the fluids of interest were injected into the system and recovery factors were obtained for each system (fluid and porous media) by using the colored portion of the recorded images, which represents the hydrocarbon-occupied area. The injection rate was set at 0.001 cc/min in this set of experiments because the capillary number roughly calculated to be more than $10^{-6}$

for this injection rate and the residual oil decreased smoothly. In addition, no fluid turbulence existed in this range of injection rate.

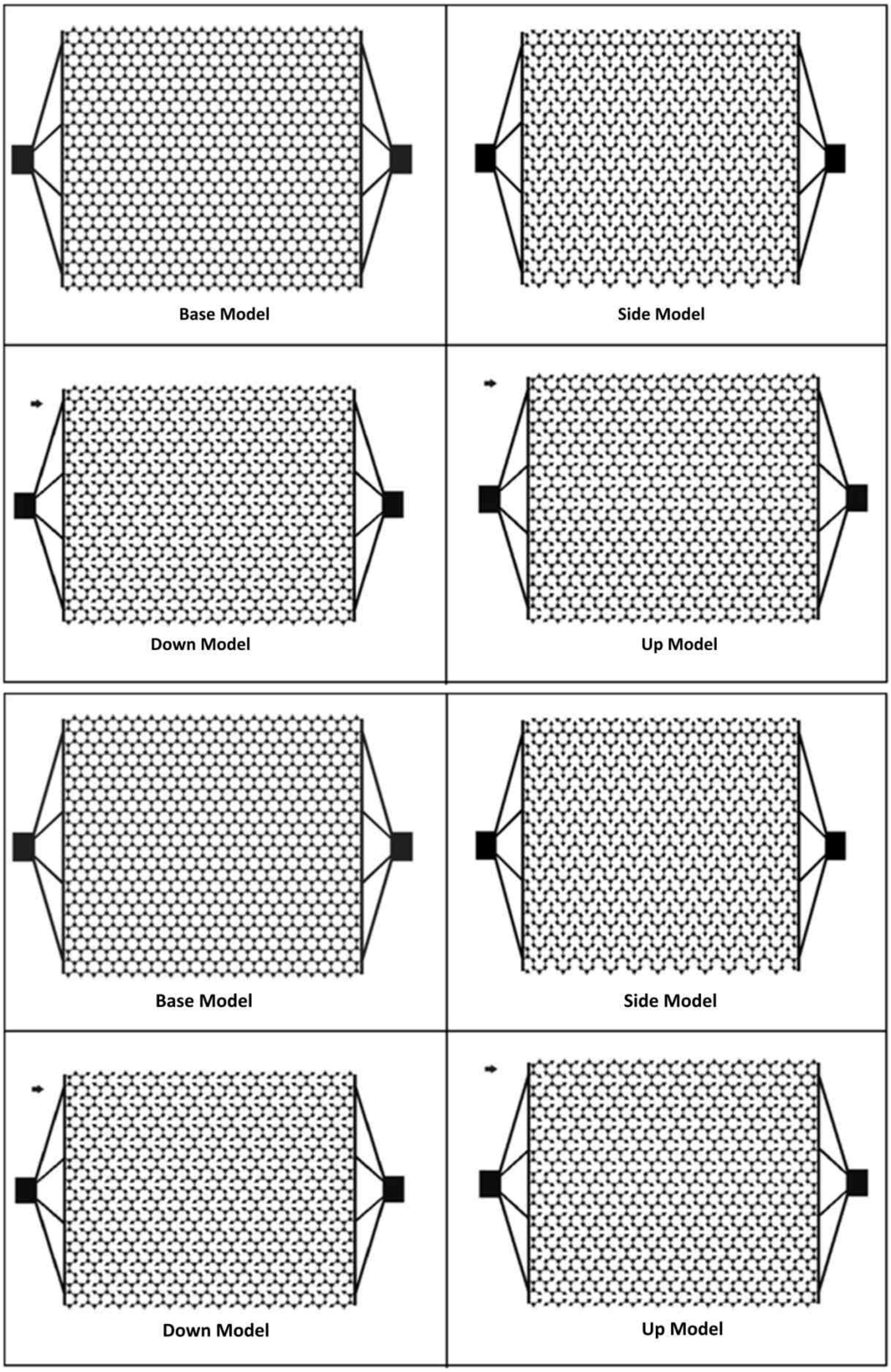

**Figure 1**
Four types of micromodels used in the experiments; base model, side model, down model, and up model

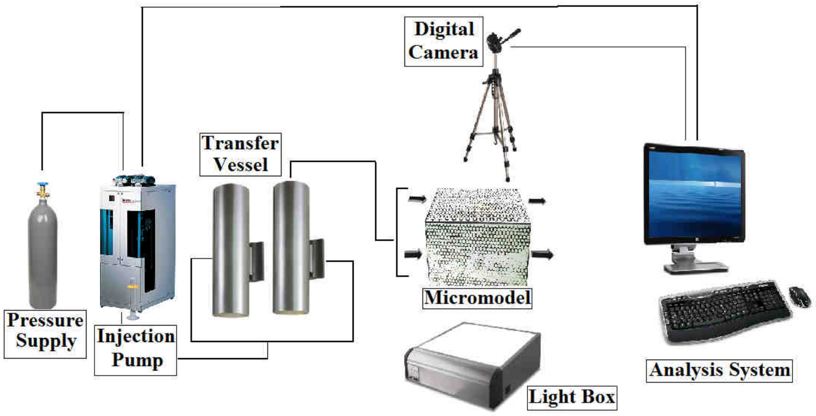

**Figure 2**
Schematic of the micromodel set-up

## 3. Results and discussion

The main role of polymer in an injection scenario is to increase the viscosity, and thereby attaining an improved mobility control of injecting fluid. If sufficient mobility control does not exist, the injecting slug fingers into the oil/water bank, which causes early breakthrough and poor sweep efficiency. The results show that polyacrylamide almost always enhances oil production recovery factor (up to 14% in comparison with brine injection) in glass micromodels.

The addition of surfactant to the injecting fluid reduces the interfacial tension (IFT) of water/oil system, and hence decreases capillary forces. The IFT between the brine and the oil can be decreased $10^4$ times by surfactant addition.

Alkali in chemical flooding has two main objectives, namely increasing the pH so as to decrease surfactant adsorption by increasing the negative charge on the rock surface and producing in-situ natural surfactant and making the process economic by lessen the needed surfactant.

In this study, at first, the effect of injecting chemicals (Table 1) on the recovery factor is investigated and then the impact of dead-end pores orientation with respect to the flow direction is observed. Four distinct glass micromodels have been designed for performing experiments including base model, which has no dead-end pores, side model, which has dead-end pores perpendicular to flow course, up model, which has dead-end pores parallel with the flow, and down model, which has dead-end pores against the flow direction (Figure 1).

### 3.1. Results of injecting different chemicals in the side model

In this series of experiments, 17 different injection fluids of different alkaline (sodium carbonate), surfactant (sodium dodecyl sulfonate), and polymer (polyacrylamide) concentrations were generated. All the fluid concentrations are listed in Table 1. Due to the analysis of the impact of polyacrylamide (PAM) concentration on recovery factor, two different concentrations of PAM were injected into the side model. PAM with a concentration of 1200 ppm has a longer breakthough time and also a higher recovery factor than the PAM with a concentration of 600 ppm (Table 1, Figure 3). The main application of surfactants in enhanced oil recovery is to lower the interfacial tension between an aqueous solution and oil phases. Observing the effect of surfactant concentration on the oil recovery shows that increasing the sodium dodecyl sulfonate (SDS) concentration gives better microscopic efficiency; however, reducing the SDS concentration without increasing the viscosity causes early breakthrough and thus lowers recovery factor (Table 1, Figure 3).

**Table 1**
Recovery factors of different fluids in various porous media

| **Model** | | | | | **Side** | **Base** | **Down** | **Up** |
|---|---|---|---|---|---|---|---|---|
| **Material** | **$Na_2CO_3$ (ppm)** | **SDS (ppm)** | **PAM (ppm)** | **NaCl (ppm)** | **RF (percent)** | **RF (percent)** | **RF (percent)** | **RF (percent)** |
| ASP1 | 10000 | 2000 | 1200 | 10000 | 56 | 69 | 44 | 60 |
| ASP2 | 10000 | 2000 | 600 | 10000 | 48 | - | - | - |
| ASP3 | 10000 | 1000 | 1200 | 10000 | 55 | - | - | - |
| ASP4 | 10000 | 1000 | 600 | 10000 | 40 | - | - | - |
| ASP5 | 5000 | 2000 | 1200 | 10000 | 66 | - | - | - |
| ASP6 | 5000 | 2000 | 600 | 10000 | 22 | - | - | - |
| ASP7 | 5000 | 1000 | 1200 | 10000 | 51 | - | - | - |
| ASP8 | 5000 | 1000 | 600 | 10000 | 75 | 52 | 67 | 56 |
| S1 | 0 | 2000 | 0 | 10000 | 27 | - | - | - |
| S2 | 0 | 1000 | 0 | 10000 | 42 | - | - | - |
| P1 | 0 | 0 | 1200 | 10000 | 60 | - | - | - |
| P2 | 0 | 0 | 600 | 10000 | 29 | - | - | - |
| S1P1 | 0 | 2000 | 1200 | 10000 | 56 | - | - | - |
| S1P2 | 0 | 2000 | 600 | 10000 | 49 | - | - | - |
| S2P1 | 0 | 1000 | 1200 | 10000 | 50 | - | - | - |
| S2P2 | 0 | 1000 | 600 | 10000 | 39 | - | - | - |
| Brine | 0 | 0 | 0 | 10000 | 46 | 47 | 46 | 24 |

In a surfactant/polymer flooding process, both microscopic and macroscopic efficiencies will improve. The fluid with higher concentrations of both SDS and PAM (S1P1) has the best recovery among these set of chemicals. S2P2 has the weakest recovery in this series (Table 1, Figure 4).

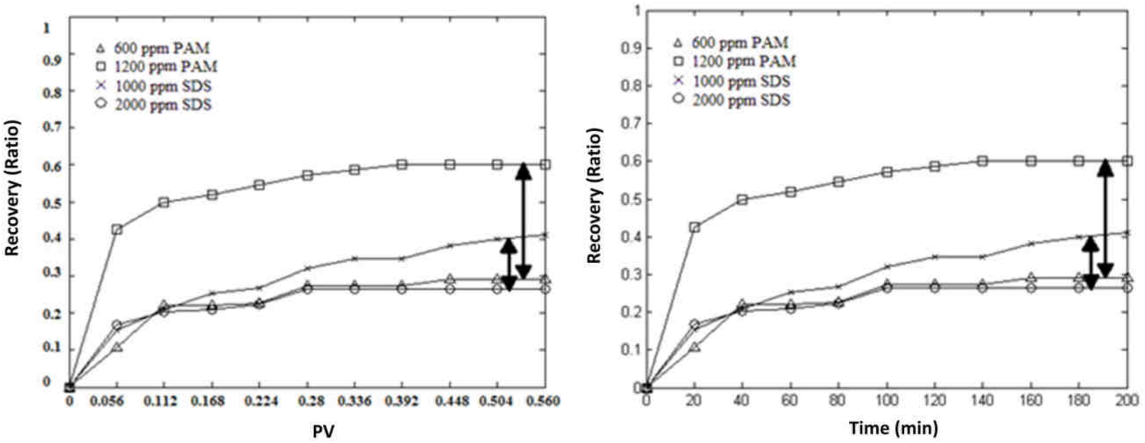

**Figure 3**
Effect of different concentrations of PAM and SDS on oil recovery in side model

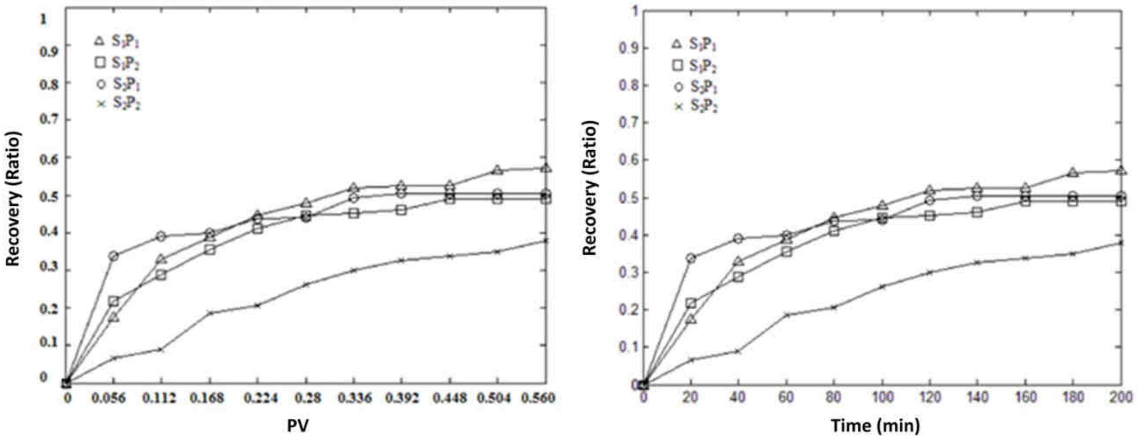

**Figure 4**
Effect of SDS-PAM (SP) injection on oil recovery in side model

In an ASP process, any increasing in the polymer concentration directly impacts on recovery factor, but the degrees of these effects are different. Remarkable difference between ASP5 and ASP6 shows that at low concentrations of $Na_2CO_3$ and high concentrations of SDS changing polymer concentration has the most marked effect on oil recovery. The minimal effect has been observed at low concentrations of both $Na_2CO_3$ and SDS (ASP7 and ASP8) (Table 1, Figure 5). At high concentrations of PAM in ASP flooding, increasing the SDS concentration improves the recovery factor (compare ASP5 and ASP7); but at low concentrations of PAM, SDS has an inverse effect on ultimate recovery (compare ASP6 and ASP8). This phenomenon has occurred because of viscous fingering and early breakthrough (Table 1, Figure 5). Moreover, in all cases, the combination of low PAM concentration and high SDS concentration increases the alkaline concentration, which has an inverse effect on recovery factor (ASP2 and ASP6). Comparing the recovery factor of the ASP1 and ASP5 cases shows the inverse effect of increasing $Na_2CO_3$ concentration on recovery factor (Table 1, Figure 6).

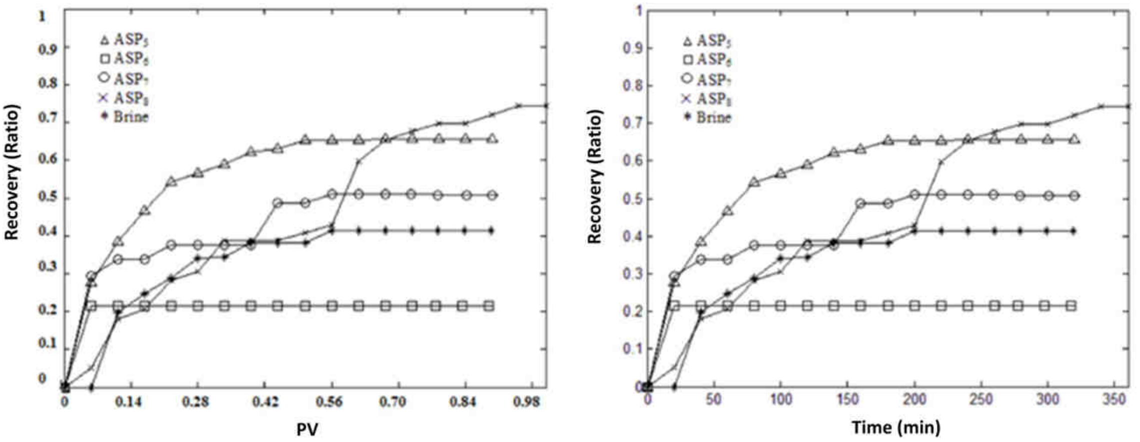

**Figure 5**
Effect of different concentrations of PAM and SDS on oil recovery factor in side model

### 3.2. Effect of Dead-end pore orientation on recovery factor for ASP1, ASP8, and brine injection

In ASP1 injection, the base model shows the best recovery among all models. The side model sits in the second place. Up and down models come third and fourth respectively (Table 1, Figure 7). In the case of injecting ASP8, the best recovery factor belongs to the side model. Down, up, and base models lead to the next highest recovery factors respectively (Table 1, Figure 8). For brine injection, the base, down, and side models have respectively the highest recovery factor and are close together; but the recovery factor of up model is much lower than the other models (Table 1, Figure 9).

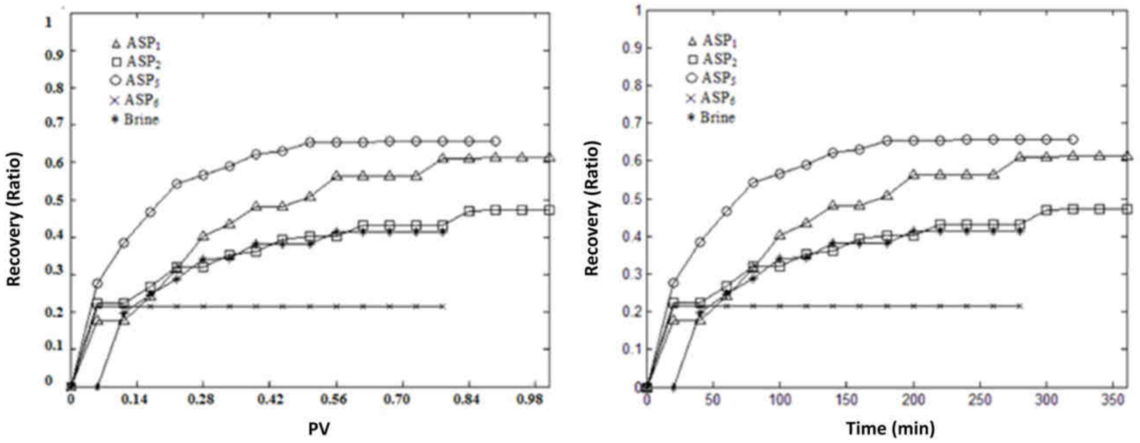

**Figure 6**
Effect of $Na_2CO_3$ concentration on oil recovery factor in side model

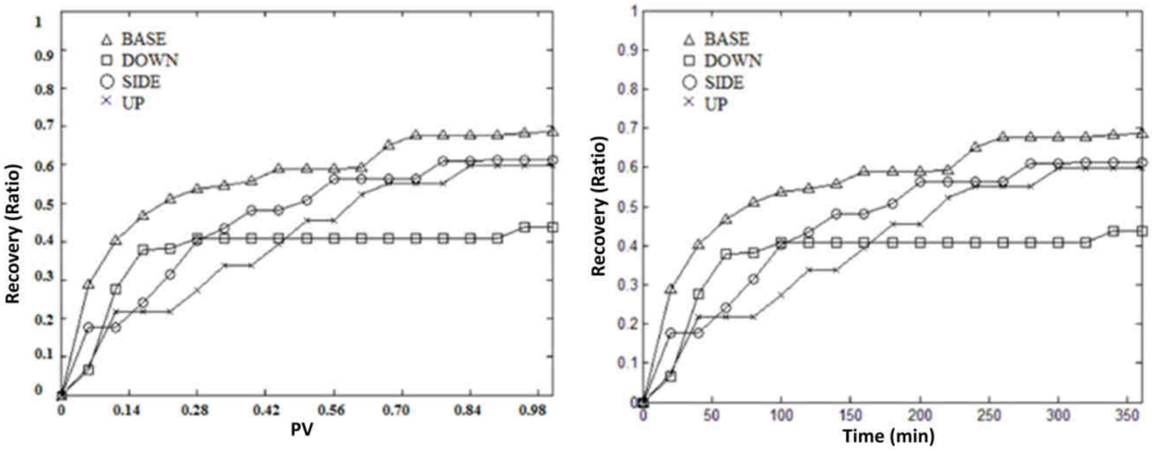

**Figure 7**
Effect of dead-end pore orientation on oil recovery factor in ASP1 injection in different micromodels

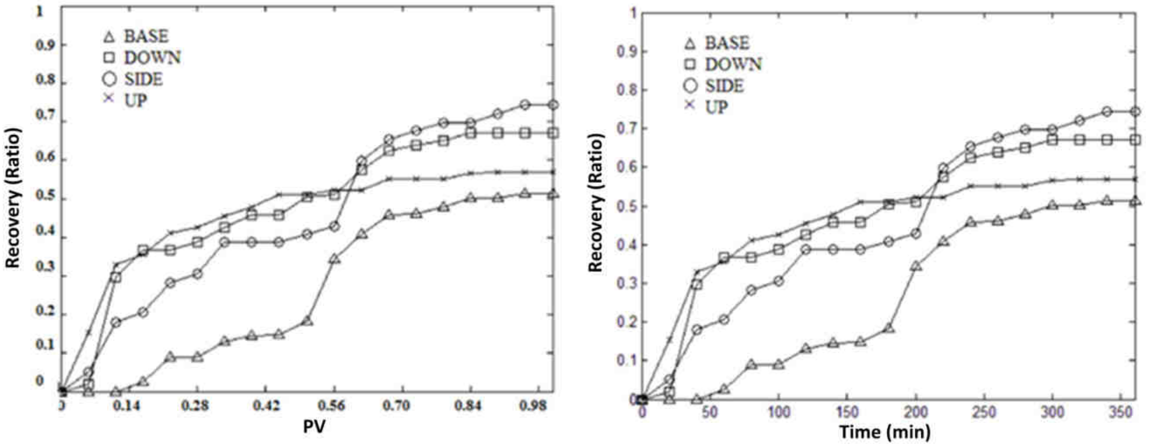

**Figure 8**
Effect of dead-end pore orientation on oil recovery factor in ASP8 injection in different micromodels

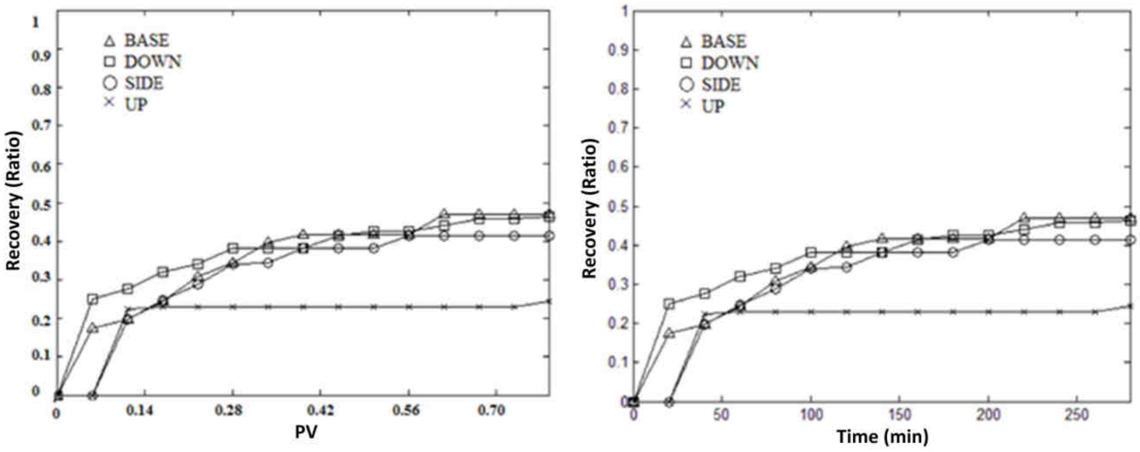

**Figure 9**
Effect of dead-end pore orientation on oil recovery factor in brine injection in different micromodels

## 4. Conclusions

In this work, flooding performances of water, polymer, surfactant, and ASP injection into glass micromodels including dead-end pores were investigated and the following conclusions can be drawn:

1. Polymeric solutions in the presence of surfactant and alkaline increase the ultimate recovery; however, the amount of increase in recovery in these solutions are less than polymeric solutions without using surfactant and alkaline.
2. Increasing SDS concentration up to its CMC usually improves recovery; but in some cases (low concentrations of both PAM and $Na_2CO_3$) it causes inverse results.
3. Depending on PAM, SDS, and $Na_2CO_3$ concentrations, ASP flood can improve or deteriorate the recovery performance.
4. In ASP1 injection, the base model has the best recovery among all the tested models. Side model sits in the second place. Up and down models come third and fourth respectively.
5. In the case of injecting ASP8, the best recovery belongs to the side model. Down, up, and base models lead to the next highest recovery factors respectively.
6. In brine injection, the base, down, and side models have respectively the highest recovery factors and are close together, but the recovery factor of up model is much lower than the other models.

## Nomenclature

| | |
|---|---|
| ASP | : Alkaline surfactant polymer |
| CIPS | : Calcite in-situ precipitation system |
| IFT | : Interfacial tension |
| O/W | : Oil-in-water |
| ppm | : Part per million |
| PAM | : Polyacrylamide |
| RF | : Recovery factor |
| SDS | : Sodium dodecyl sulfonate |

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