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The study of flow through porous media within the near-slot region of SAGD operations using PSV

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Abstract

Steam-assisted gravity drainage (SAGD) is a technique used for oil sand recovery in Alberta. Oil sand is a composition of sand, clay, water and bitumen. A slotted liner is used in SAGD operations to allow multiple phases flows to be produced, passing the flow through narrow slots throughout the length and circumference of the liner, which minimizes sand production. The objective of this research is to examine the phenomena that occur in the near-slot region to investigate the influence of flow characteristics on slot failure. A particle shadowgraph velocimetry (PSV) experimental set-up in conjunction with image processing techniques were used to investigate the effect of the presence of porous media on the flow field and the build-up of particles in the near-slot region. The experiments were performed with a single slot under two conditions, the flow into a single straight slot and a slot with an inlet condition aimed to simulate porous media. This study shows that particle shape at the micro scale and the presence of porous media affects the transport of particles in the near-slot region.

1 Introduction

Oil sand is a mixture of sand, clay, water and bitumen, has a high viscosity (> 10,000 cP) and is immobile under reservoir conditions (Speight 2013). Steam-assisted gravity drainage (SAGD) is a technique used for bitumen recovery. The process involves two horizontal wells drilled into the oil sands formation. Steam is injected through the upper well, heats the oil sand reduces its viscosity and the 'liquefied' bitumen drains into the lower well to be produced to the surface (Etherington and McDonald 2004). A slotted liner, used as a sand control device in SAGD operations, is a pipe with multiple narrow slots throughout its length and circumference that limits the migration of sand particles into the production well. There are a number of different failure mechanisms that are related to changes of the properties of slots. These include scale formation, fouling, particle buildup and plugging at the entrance and throughout the length of the slot. Particle build-up occurs due to the transport of 'fines' or particles < 44 µm (Mahmoudi et al. 2015), referred to as fines migration, into the region of the slot and buildup occurs due to changing conditions in the flow field.

Fines migration can occur within the reservoir where mobile particles eventually settle and plug the pore throats within the formation, decreasing the permeability and productivity of the formation (Xie et al. 2014). However, reduction in productivity can also occur in the near-slot region, which is the transition area from the reservoir to the entrance of the slots. This is due to the migration and build-up of the fines causing a decrease in the open flow area in the near-slot region. The surface and geometric properties of the fines can influence the particle build-up effect and the consequent reduction in productivity.

The objective of this study is to investigate phenomena that occur in the near-slot region. The work in this paper presents the flow field through porous media and the build-up of particles in the near-slot region with a single slot using particle shadowgraph velocimetry (PSV). An understanding of these phenomena is essential in the development of any model that describes fines migration in the near-slot region in SAGD operations for predicting slot performance and failure.

2 Experimental Setup

The PSV measurement system used to visualize the flow field and transport of fines in the near-slot region through a single slot is shown in Figure 1(a). An LED light source (BX0404 Green, Advanced Illumination Inc.) provided uniform back illumination of the region of interest. A high speed camera (SP-5000M-PMCL, JAI Inc.) with a macro lens (105 mm f/2.8, Sigma) captured the flow of the multiphase fluid. A function generator (AFG 3022B, Tektronix Inc.) was used as a timing device to trigger the camera to capture images at a frequency of 85 frames per second. In general, an exposure time of 70 µsec was used on the camera to freeze the motion of flow.

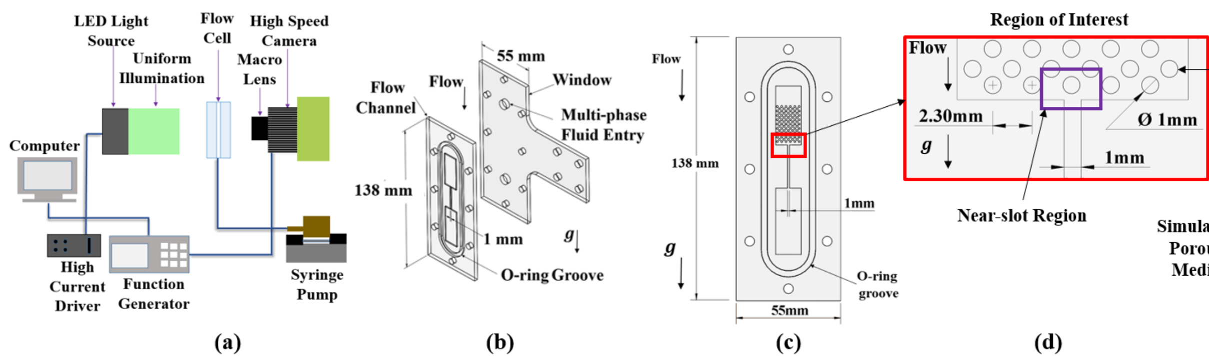


Figure 1: (a) The PSV experimental set-up schematic (b) The solid model assembly of the flow cell (c) The solid model of the flow channel –Note two conditions were used; flow into a the straight slot only and a slot with an inlet condition aimed to simulate porous media (d) The region of interest or field of view of the camera and near-slot region used in the analysis.

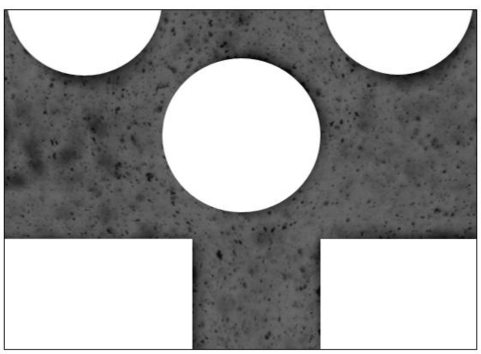
The geometry of the flow cell used in the experiments is shown in Figure 1. It was mounted vertically and a sandwich of the flow channel and a transparent window was used to make the complete flow cell as shown in Figure 1 (b). The window as shown in Figure 1 (b) was made of acrylic sheet and fabricated with a laser cutter (VLS3.50, Universal Laser). The flow channel was manufactured using an additive manufacturing process (Form 2, Formlabs Inc.) from a clear photopolymer resin. This manufacturing technique for the flow channel was preferred as it allowed the manufacturing of complex flow geometries, such as porous media, in a controlled manner for this study. There are multiple slot profiles design that are used in SAGD operations including straight slots, rolled slot and keystone (Bennion et al. 2009). For the purpose of this study the slot profile was limited to the straight slots. The experiments were performed using two flow cells with two different conditions, the flow into a single straight slot and a slot with an inlet condition aimed to simulate porous media as shown in Figure 1 (c). The latter flow channel was designed with equally spaced pillars (1mm diameter and 1mm height) to simulate a porous media region at the slot entrance. The region of interest in this study, which is also the field of view of the camera, is shown in Figure 1 (d). However, the focus of all the analyses in this study was in the near-slot region in the field of view as shown in the highlighted section in Figure 1 (d).

The fluid used in the experiments was a 72 wt% glycerol/water solution with the viscosity of 27.7 cP obtained from the aqueous solutions of glycerol tables in (Segur et al. 1951). Two shapes of particles, spherical and irregularly shaped, were used in this study to represent the fines found in oil sand reservoirs. These include 40 µm silicon carbide irregularly shaped particles (AGSCO Corp.) or 40 µm polystyrene spherical microbeads (Dynoseeds TS40, Microbeads AS) considered as fines. 2 µm silver coated silica particles or 4 µm polystyrene microbeads were used as tracer particles to analyze the flow for the irregularly shaped particles and spherical particles, respectively. Each solution consisting of glycerol/water, ‘fines’ and tracer particles were placed on a magnetic stirrer (PC-353, Corning) to ensure the seeding density was consistent throughout the fluid. The fluid was injected at the top of the flow cell with a controlled flow rate scaled to SAGD production conditions of 10 ml/hr using a syringe pump (70-2208 11 plus, Harvard Apparatus Inc.), in the same direction as gravity. All the images were collected and saved in a designated computer for image processing.

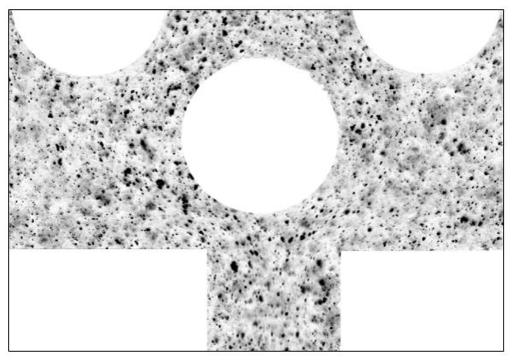
3 Image Processing

Detection of particles that represents the fines was the first step in the image processing. This was also the most essential step to analyze the fines migration in the near-slot region. In this study, the differences between the respective intensities of the particles and the remaining area were used to detect the particles (Kinsale et al. 2017). Intensity differences were also utilized to identify regions of particle build-up.

Particle image velocimetry (PIV) image processing was used to interrogate and define the velocity field in the near-slot region using a commercial software (DaVis 8.3.1 LaVision GmbH). Image pre-processing techniques applied to the raw images included a subtract sliding minimum filter to remove/reduce the background noise in the images. This filter allows all the particles to appear dark on a light background as shown in Figure 2. A sliding average calculation was then used to determine the average flow field. A multi-pass cross correlation with interrogation windows of 96 × 96 pixel followed by 48 × 48 pixels were used to determine the velocity vector field. An in-house post-processing code (Matlab, The MathWorks Inc.) was used for post-processing and plotting of data.



(a)



(b)

Figure 2 The outcome of using the sliding minimum filter (a) The raw image (b) The pre-processed image

4 Results and Discussion

In this study the flow fields for two scenarios were considered. The flow into an open slot without and with the presence of porous media in the inlet region. The flow channel described in section 2 was designed with equally spaced pillars so as to simulate the near wellbore porous media in oil sand reservoirs.

Using the tracer particles only, the velocity field in these two scenarios were obtained from the PSV measurement. The average velocity distributions for each case are shown in Figure 3. The comparisons of the phenomena observed from Figure 3 (a) and (b) match with the corresponding fundamental theory. The flow field in the open slot scenario Figure 3 (a) was symmetric, having a uniform convergence of the flow. The velocity also increased in the near-slot region; this is due to the change in cross-sectional area at the entrance of the slot. A parabolic velocity profile observed within the slot and zero velocity at the wall of the slot also agreed with expectations. However, the flow field in Figure 3 (b) was more dispersed compared to Figure 3 (a) due to the presence of porous media. In the region before the slot within the porous media, the relative maximum velocity occurred within the pore spaces with minimum velocity around the outer walls of the pillars. The flow characteristics observed indicated the reliability of the PSV measurement system to obtain measurements that agree with fundamental theories.

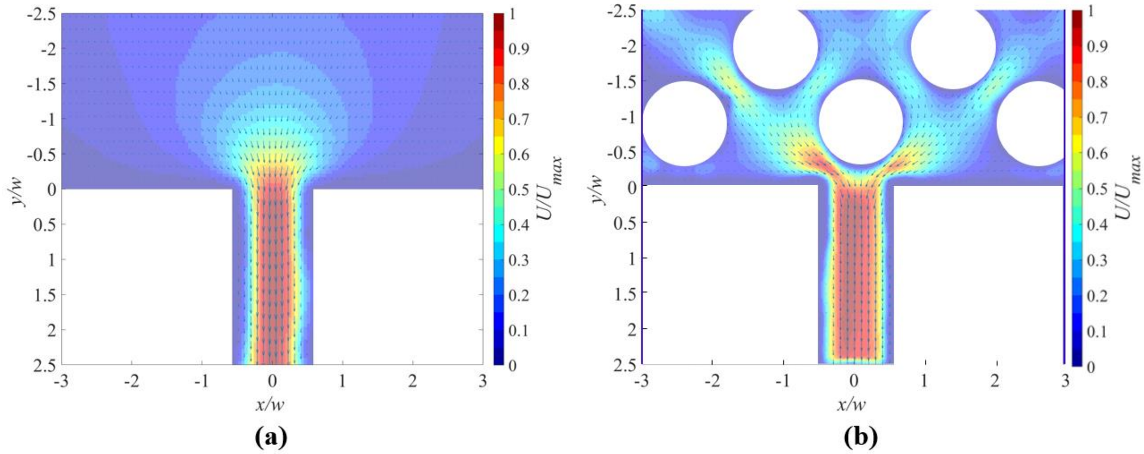


Figure 3 The velocity field within the region of interest for (a) the straight slot (b) the straight slot with the inlet condition that simulates porous medium. Both plots were normalized with respect to the width of the slot.

The next phase of the analysis was to determine the factors that influence particle build-up in the near-slot region, again using both cases of the straight slot without and with the porous media inlet condition. The analysis included two types of particles that represented the fines in the oil sand reservoirs namely, 40 µm spherical microbeads and 40 µm irregularly shaped particles. The results were used to deduce the effect of particle shape on the build-up at the entrance of the slot. Figure 4 shows the results for the spherical microbeads. Results for cases with the straight slot without and with the porous medium are shown in Figure 4 (a) and (b), respectively. While the large 40 µm are clearly evident in the images compared to the 4 µm tracer particles, for both scenarios, no significant build-up was observed.

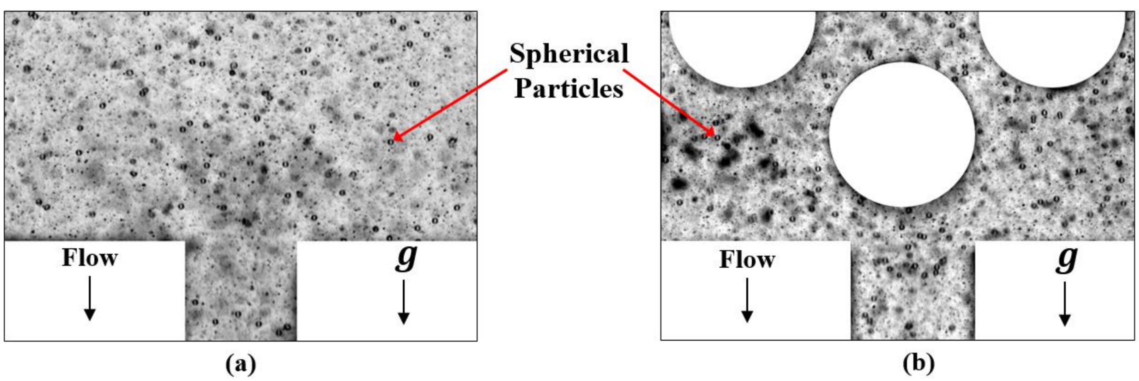


Figure 4 The flow of the 40 µm spherical microbeads in the near-slot region for (a) the straight slot (b) the straight slot with the inlet condition that simulates porous medium.

Figure 5 shows the results for the irregularly shaped 40 µm particles. The images highlight the relatively large scale of these particles compared to the 2 µm tracer particles used in this case. In Figure 5 (a), a thin layer of particle build-up can be seen at the surface of the slot entrance. However, with the porous media present, Figure 5 (b), significant particle build-up was observed both at the leading front of the porous media as well as the entrance to the slot.

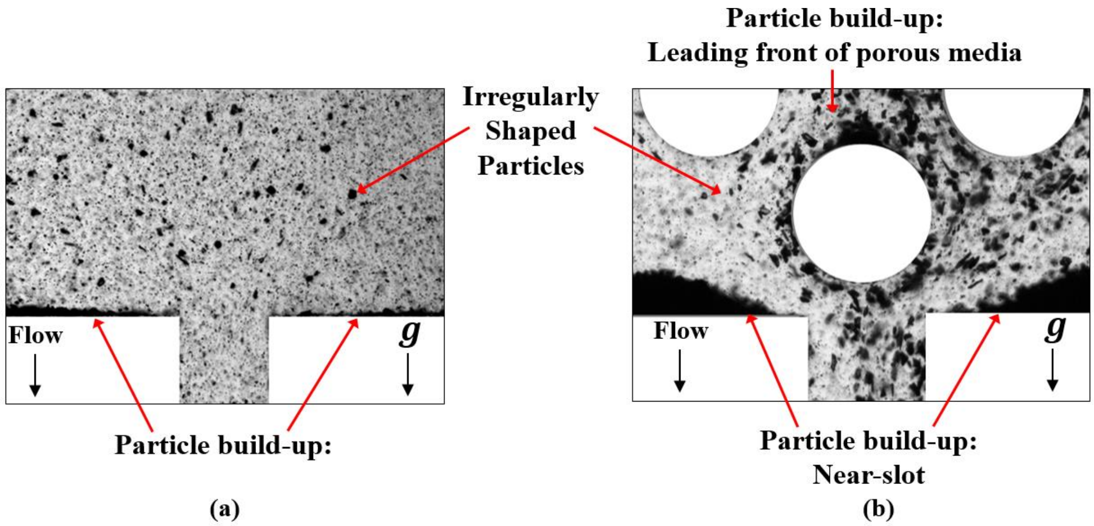


Figure 5 The flow of the 40 µm irregular shape particles in the near-slot region where particle build-up was observed for (a) the straight slot (b) the straight slot with the inlet condition that simulates a porous medium.

The results indicate that particle shape and the presence of porous media affects particle build–up. It was noted in **Error! Reference source not found.** that no build-up occurred for the spherical particles without and with porous media at the inlet. The spherical particles that fell on the surface of the entrance of the slot were more likely to follow the flow rather than build-up at the entrance compared to the irregularly shaped particles. For the irregularly shaped particles in Figure 5, build-up was observed in both cases. This suggested that the irregularly shaped particles had strong interlocking. This minimized the flow potential of the bed of particles to flow along the surface of the entrance of the slot. The porous medium also influenced the amount of particle build-up as shown in Figure 5 (b). The flow path specified by the presence of the porous medium matrix is a possible factor for the accumulation of particles in the inlet region. The build-up that occurred at the leading front of the porous medium caused aggregations of particles to be suspended into the flow. Some of these clumps of particles fell on the surface of the slot which contributed to build-up.

Another goal of this study was to understand how the fines affect the flow regime. In order to accomplish this, an algorithm mask was used to mask out the larger particles to determine the flow field around them. Figure 6 shows the processed image of the velocity vector field for the movement of the 40 µm irregularly shaped silicon carbide particles in the near-slot region.

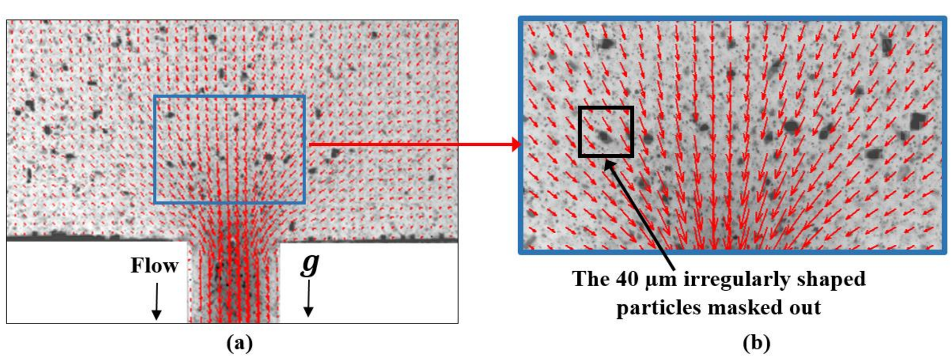


Figure 6 (a) The flow field around the 40 µm irregularly shaped silicon carbide in the near slot region. (b) An illustration of the effect of the algorithm mask to mask out the bigger particles.

This shows that the experimental and image processing methodologies described in this paper are capable of capturing the flow field around particles of this size scale. However, a greater magnification and smaller tracer particles are required for a detailed study to visualize the movement of the fluid around the particles.

5 Conclusion

This work is aimed to provide a better understanding of multiple phase flow through narrow-slots under conditions relevant to the SAGD process. A wider ranging study will provide a basis for developing analytical theory for analyzing fines migration in real time. A PSV measurement system and image processing techniques were used to visualize and analyze the flow field in the near-slot region though a single slot in two cases without and with an inlet condition which simulates porous media. The results were comparable to theory which proves the reliability of the PSV measurement system to obtain the flow field in the near-slot region. The experiments were performed using 40 µm spherical polystyrene microbeads and irregularly shaped 40 µm silicon carbide particles and. By comparison of the results in these two cases, it was observed that particle shape affects the transport of particles in the near-slot region and particularly with the presence of porous media before the inlet of the slot. The particle build-up occurred for the irregularly shaped particles and not for the spherical ones. The build-up of particles indicates that with continuous flow over time the potential plugging of the slot may occur naturally. The experimental results obtained in this study provide a good foundation to achieve the ultimate goal of this research, which is to model fines migration in the near-slot region as it occurs with time in SAGD operations.

Acknowledgements

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