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Fiber Optics Application for Downhole Monitoring and Wellbore Surveillance; SAGD Monitoring, Flow Regime Determination and Flow Loop Design

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Abstract

Effective Steam Assisted Gravity Drainage (SAGD) operation relies on subcool management to reduce the risk of steam breakthrough. Monitoring of several parameters is performed to assure uniform development of steam chamber and heating of reservoir. This paper discusses the application of Distributed Acoustic Sensing (DAS), a monitoring platform to achieve reliable reservoir and wellbore surveillance in SAGD projects.

In this study, a comprehensive review of DAS deployment in oil and gas industry was performed including vertical seismic profiling, hydraulic fracturing, well/pipe integrity and flow profiling applications. Then, SAGD flow monitoring was investigated in detail. To utilize DAS in SAGD projects, knowing completion designs are necessary. Therefore, various SAGD completion designs and corresponding flow regimes were discussed as well. Finally, four flow loop designs were proposed to accurately simulate the complex wellbore hydraulics of the SAGD producer using DAS recordings.

This work started with an overview of DAS systems in downhole monitoring including real time high resolution vertical seismic profiling, hydraulic fracturing characterization and optimization, well and pipe integrity, leak detection and assessing completion effectiveness. Then, flow profiling including flow rate, flow fractions and flow regimes determinations using DAS were discussed with focus on SAGD monitoring. Completion designs directly impact on SAGD monitoring and DAS recordings, more specifically on flow regimes inside the tubing and annulus. Therefore, various completion designs with their tubing and screen sizes were presented and corresponding flow regimes were determined in both tubing and annulus. It was observed that flow regimes vary with type of completion design, liquid flow rate, steam breakthrough locations and tubing/screen sizes. Eventually, four flow loop designs were proposed based on the discussions for future DAS application.

This paper discusses existing completion designs and possible flow regimes in SAGD projects. Consequently, novel designed flow loops are introduced for DAS deployment to better understand the complex wellbore hydraulic of the well and measure the key parameters in optimizing the production operation. This study is a design stage for future quantitative measuring of flow profiling using DAS systems.

Keywords:: Distributed Acoustic Sensing, Reservoir Surveillance, SAGD Completion Designs, Flow Regime, Flow Loop

Introduction

In the last decades, the fiber-optic sensing technologies have received vast attention from Exploration and Production (E&P) companies. Their increased reliability and reduced cost allowed many companies to select fiber-optic based technologies as the downhole instrumentation of choice for several projects. Typically, a carbon rod containing fiber optic cable is pushed through the total depth/length of well in order to measure accurately the temperature and vibration along the entire well with a spatial resolution down to one meter. The utilization of optical fiber technology in data acquisition and monitoring has many advantages over conventional approaches. They are immune to electromagnetic interference because electronic transducers and circuit boards are not required to be installed in the well anymore. They can work at high temperature condition (greater than 150°C) and they are able to make distributed measurements of temperature, strain and vibration (Tatiana, 2014).

The variation of live property as a function of time is monitored by various fiber optic sensing devices, such as distributed acoustic sensing (DAS), distributed temperature sensing (DTS), distributed chemical sensing (DCS), distributed pressure sensing (DPS), distributed strain sensing (DSS), and distributed vibration sensing (DVS). All these instruments provide the arrays of data points as a function of time and location because of their distributed sensing nature.

The DCS, DPS, DSS, and DVS have mainly been used for specific fluid molecule determination, fluid level determination, compaction monitoring, and disturbance/vibration signature location monitoring, respectively. Distributed Temperature Sensing (DTS) is one fiber-based technology which accurately measures a wide range of temperatures in harsh environments. The DTS technology has been used in various areas such as conducting reservoir surveillance, steam and water injection monitoring and gas lift system optimization, real-time monitoring of acid stimulation, tracking and surveillance during production and shut-in periods, and downhole leak detection (Tatiana, 2014).

The DAS technology has many practical applications such as monitoring in-well activities and hydraulic fracturing treatment, vertical seismic profiling, well integrity, and wellbore injection and production surveillance and profiling. There are some common applications for both DAS and DTS where in some operations the simultaneous deployments are recommended for a comprehensive surveillance. This paper details the improvement, advantage, disadvantage and limitations of DAS application in the literature for over two decades. Then, its application in SAGD wells is assessed, existing completion designs and corresponding flow regimes are determined and subsequent flow loop designs are proposed.

Distributed Sensing Basics

A laser source is used to emit pulses through the optical fibers and the backscattering light is analyzed to obtain the distributed information with high resolution. Figure 1 shows three types of light scattering received in distributed sensing devices. The DAS works based on the processing of Rayleigh scattering, while DSS and DTS analyze Brillouin or/and Raman scattering to provide high resolution distributed properties.

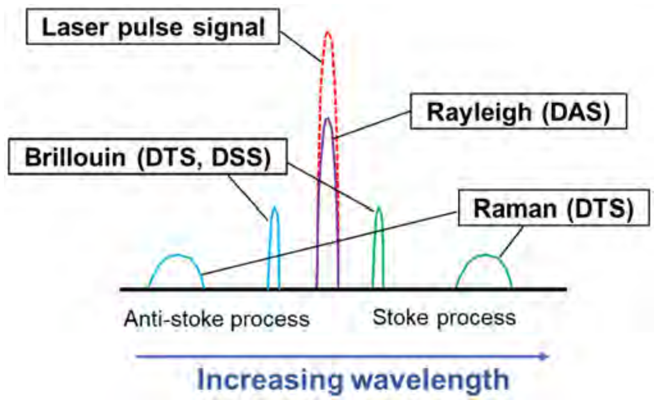

Figure 1—Scattering lights (Rayleigh, Brillouin, and Roman)

The elasticity of light scattering is defined based on the energy of signal. If the energy (wavelength) of the scattered photon is the same as the signal photon, the light scattering is elastic (e.g. Rayleigh scatter), otherwise it is inelastic (e.g. Brillouin and Raman scattering). Among three types of light scattering, Rayleigh has the strongest absorption signal and high signal-to-noise ratio (SNR) which is a significant parameter in the application of DAS systems. The intensity and wavelength of Brillouin scattering, both stokes (green) and Anti-stokes (blue) signals, are associated with the strain and temperature.

The wavelengths of Brillouin scattering (both stokes and Anti-stokes) are placed very close to the emitted signal, which require sophisticated filtering approach to remove the Rayleigh signal and elevate SNR. The strain and temperature can be characterized through the processing of Brillouin scattering by using DSS and DTS, respectively. The wavelengths of Roman scattering (both stokes and Anti-stokes) are broadly separated which leads to convenient filtration of Rayleigh scattering and enhance SNR. Most DTS systems analyze the Roman scattering because not only it needs easy filtration, but also it is insensitive to the strain. The only disadvantage of Raman scattering is related to their weak signal intensity. The larger input signals are recommended to increase the intensity of Raman signal.

As a result, the multimode fibers, the passage of multiple mode of light which carry more data, are suggested for the application of Raman scattering-based DTS. The single mode fibers, the passage of one mode of light which has lower noise are suggested for Rayleigh scattering-based DAS. In addition, multimode fibers are suitable for short distances due to their higher signal attenuation.

Fiber Installation

The fiber optics can be installed at different places based on the region of surveillance. There are both advantages and disadvantages for the position of fiber optics. Shoaibi et al. (2016) summarized the types of fiber optics installation in three categories including dip-in survey, semi-permanent, and permanent. In dip-in-survey installation, no workover is required in the existing wells and this type of installation can be conducted in many wells. On the other hand, it is not ideally coupled to reservoir and needs the production deferment. The dip-in-survey installation causes the intervention and consequently leads to HSE issues. The semi-permanent installation can be conducted into the existing wells, even after production. However, the difficulties such as pulling out and re-installation of this method are not economically justifiable for well lifecycle, and again not being ideally coupled to the reservoir causes some significant challenges. The permanent installation, unlike the other installations, is coupled to reservoir and it does not cause production deferment, although the challenges such as the management of control line detection located behind the casing is involved in this kind of installation.

Higginson et al. (2017) presented five types of fiber optics installation all of which fall into the categories mentioned above. Based on their recommendation, the application of bare fiber in the free fall mechanism is the best method due to the lowest risk and cost involved.

Soroush et al. (2019) illustrated three groups of installation, (1) the permanent installation located at the outside of casing, (2) the semi-permanent installation inside the annulus, and (3) the installation inside the tubing or production liner in coil tubing (Figure 2).

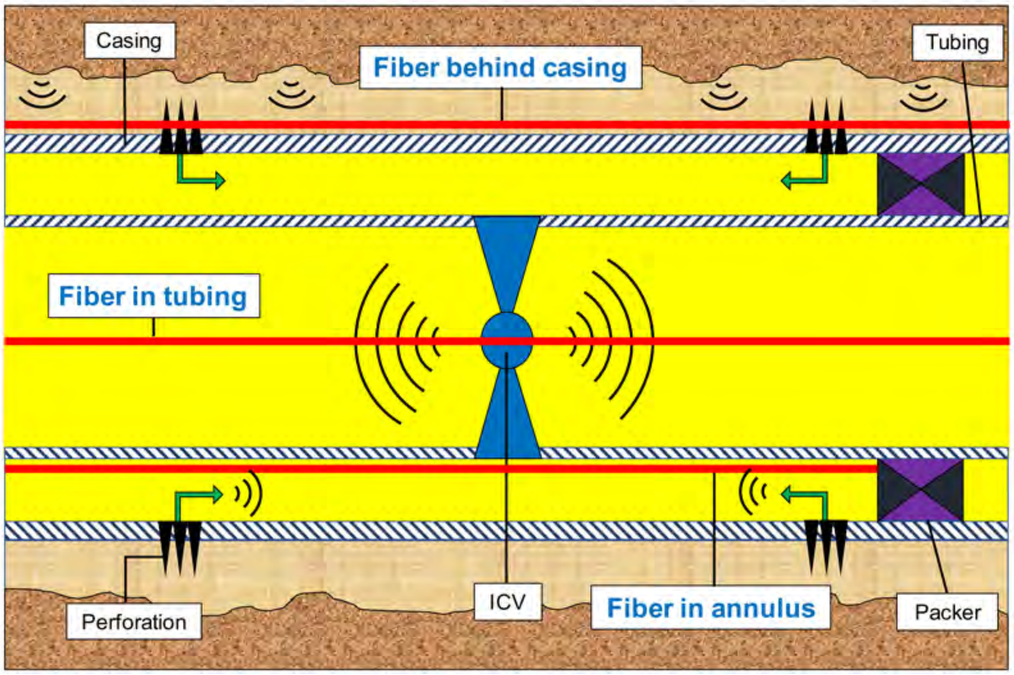

Figure 2—Fiber optics installation in the wellbore (Soroush et al. (2019))

Multicomponent DAS

DAS systems are sensitive equipment in measuring the strain in axial direction of the fiber, therefore multi-component DAS systems are required to evaluate the strain tensor. Ning and Sava (2016) recommended two different configurations for multi-component DAS, including helical optical fiber (Figure 3a) and multiple parallel optical fibers (Figure 3b). Later, Ning and Sava (2017, 2018) suggested another configuration, a combination of one straight fiber and five equally spaced helical optical fibers, which is appropriate for shorter wavelengths. This configuration, as shown in Figure 3c, helps us to obtain all the nine components of strain tensor.

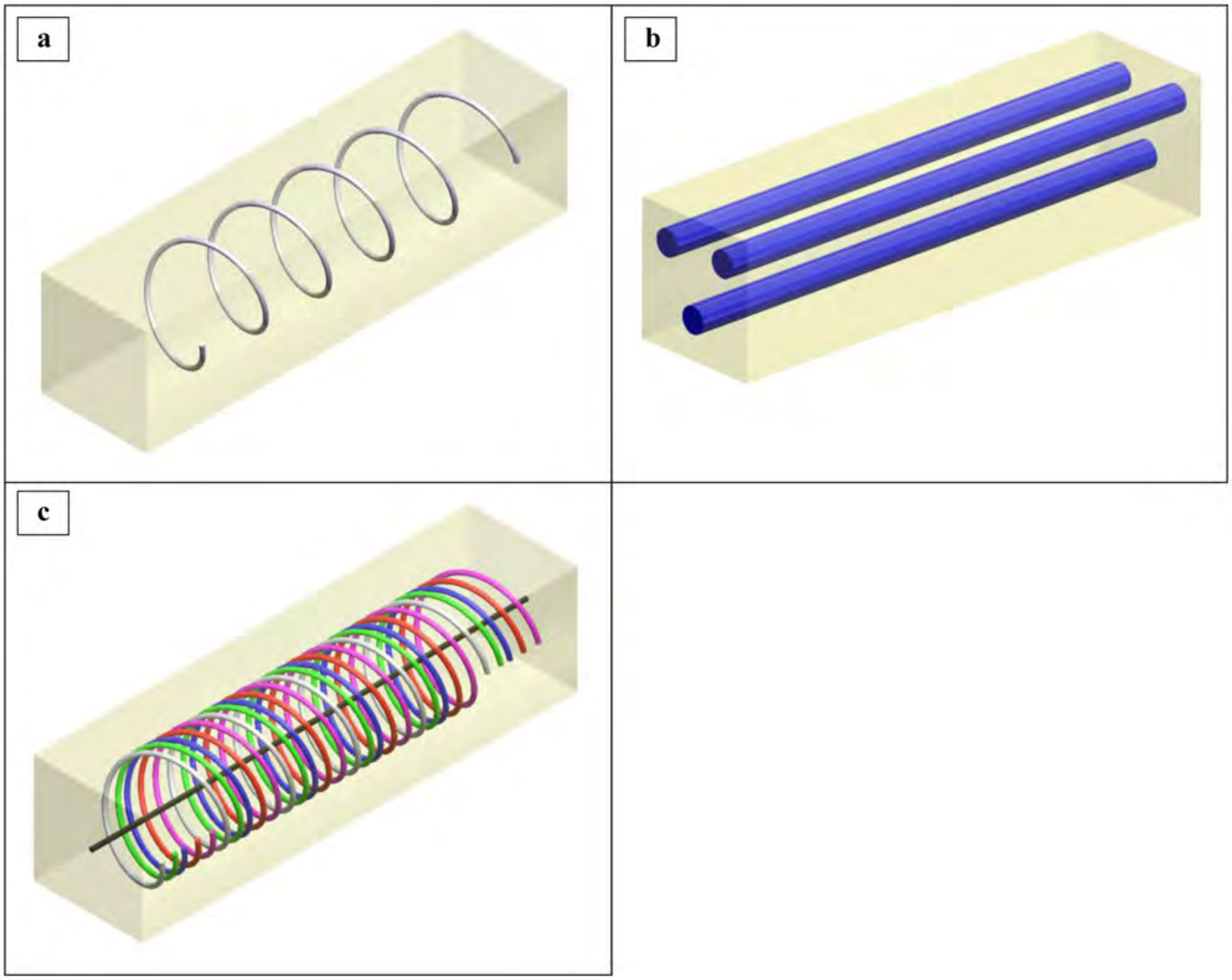

Figure 3—Multicomponent DAS configurations (a) helical optical fibers, (b) multiple parallel optical fibers (c) straight optical fiber inserted into five equally spaced helical fibers

Vertical Seismic Profiling

Seismic monitoring is carried out through the analysis of velocity models achieved from vertical seismic profiling (VSP). DAS can be used to provide seismic profiling with high spatial resolution relative to traditional equipment such as geophone. Ellmauthaler et al. (2016) indicated the agreement of DAS-VSP results with those obtained from geophone-VSP, by using two calibration points. Many investigators used DAS as a safe and cost effective tool for VSP (Mestayer et al. (2011), Mateeva et al. (2012, 2013), Bakku et al. (2014), Kendall (2014), Poletto et al. (2014), Li et al. (2015), Nizkous et al. (2015), Sanghvi et al. (2015), Zhan et al. (2015), Constantinou et al. (2016), Dou et al. (2016), Innanen (2017, 2019), Jreij et al. (2017), Kimura et al. (2017), Lopez et al. (2017), Grandi et al. (2017), Willis et al. (2017), Zwartjes et al. (2017), Bakulin et al. (2018, 2019), Kasahara et al. (2018), Spackman et al. (2018), Trainor-Guitton et al. (2018), Huot et al. (2018), Zhou et al. (2018), Alshuhail et al. (2019), Chavarria et al. (2019), Cheng et al. (2019), Ellmauthaler et al. (2019), Leaney et al. (2019), Shragge et al. (2019), Shultz and Simmons (2019), Zhang et al. (2019), Zhidong et al. (2019)).

Wilks et al. (2017) characterized the benefits of DAS-VSP relative to geophone VSP. DAS-VSP has simple installation and infrastructure, lower cost, superior depth of reach, higher resolution, continuous data acquisition, and longer durability in harsh conditions (e.g. high temperature, and chemical environment) compared to geophone-VSP. The comparison of DAS-VSP relative to geophone-VSP is detailed by other researchers (Grandi et al. (2017), Daley et al. (2014)).

In addition, Wang et al. (2019) used 3D Gaussian Beam Migration (GBM) on the data points of DAS-VSP to reduce the noise produced by the geometry of acquisition. There are many other researches regarding enhancing DAS-VSP results through the reduction of noise and improvement of SNR (Li et al. (2013), Jiang et al. (2016), Schilke et al. (2016), Yu et al. (2017), Bakulin et al. (2018), Correa et al. (2018), Gordon et al. (2018), Huot and Biondi (2018), Li et al. (2018), Naruse et al. (2018), Yu et al. (2018), Ning et al. (2019)).

Hydraulic Fracturing

The location, orientation, and hydraulic diffusivity of hydraulic fracture planes can be monitored by using DAS systems (Cole et al. (2017, 2018)). Several investigators used DAS to characterize hydraulic fracturing (Molenaar and Cox (2013), Martinez et al. (2014), Ugueto et al (2016), Somanchi et al. (2016), Stokely (2016), Kavousi et al. (2017), Meek et al. (2017), Shen et al. (2017), Starr and Jacobi (2017), Zhou and Willis (2017), Byerley et al. (2018), Eaid et al. (2018), Binder et al. (2019), Binder and Chakraborty (2019), Cramer et al. (2019), Ichikawa et al. (2019), Williams et al. (2019), Zhou et al. (2019)).

Karrenbach et al. (2017) and Webster et al. (2013) compared the application of DAS and geophone for hydraulic fracturing monitoring. Based on their studies, DAS systems provide some advantages such as continuous and high spatial resolution data points, placed near the fracture, low HSE risk, no need to have observation well, and the applicability in high pressure and temperature conditions. In contrast, they share some disadvantages, for example, they are less sensitive relative to geophone and their dependency on the direction of sensor requires multiple-component optical DAS to accurately determine the location.

Furthermore, there are many studies in which the investigators combined DAS and DTS to characterize hydraulic fracturing (Molenaar et al. (2011, 2012), MacPhail et al. (2012), Sookprasong et al. (2014), Wheaton et al. (2014), Boone et al. (2015), Gustavo et al. (2015), Holley and Kalia (2015), Wheaton et al. (2016), Hull et al. (2017), Ghahfarokhi et al. (2018), Carr et al. (2019), Jayaram et al. (2019)).

Well/Pipe Integrity

DAS can also be used to detect the pipe leakage. Distinguishing the gas leakage is easier than liquid one due to wide acoustic level of gas relative to liquid. Siebenaler et al. (2015, 2017) used DAS to investigate the leakages of liquid, gas, and multiphase flow (e.g. slug flow). A combination of DAS and DTS was also used by Thodi et al. (2014) to detect the leakage in arctic pipeline fields.

The fiber optic sensors have been temporarily and permanently installed behind the casing to identify the leakage (Boone et al., 2014). The advantages and disadvantages of this kind of fiber installation are detailed in Boone et al. (2014) study. A combination of DAS and DTS can also be employed to assess the cement and tubing-deployed completion integrity (Shirdel et al. (2017), Raab et al. (2019)).

Flow Profiling

Several investigators stated that DAS can be used for real time flow profiling along the production and injection wells and pipes. By flow profiling we mean, phase and flow regime determination and flow rate profiling (estimation) of existing phases.

Although Alfataierge et al. (2019) could only correlate flow turbulence to DAS amplitude fluctuations, some researchers (Finfer et al. (2014, 2015), Sanni et al. (2018), Rawahi et al. (2018), Hemink et al. (2016), Cerrahoglu et al. (2019)) related DAS data to flow rate. Johannessen et al. (2012) evaluated flow rate by estimating the speed of sound and Paleja et al. (2015) estimated bulk flow by slug tracking and fluid composition by speed of sound estimation. In addition, some researchers used machine learning approaches to relate acoustic signals to flow rate, for instance, Park et al. (2018) used regression techniques, Fidaner (2017) utilized wavelet transform and artificial neural network, Alkhalaf et al. (2019) used decision tree, adaptive boost and random forest, Ghahfarokhi et al. (2018) applied multilayer perceptron neural network, and Bhattacharya et al. (2019) employed Random Forest (RF), artificial neural network (ANN) and support vector machine (SVM).

Some researchers utilized DAS to estimate phase fractions (Bukhamsin and Horne (2016), Naldrett et al. (2018)), gas breakthrough (Fitzel et al. (2015)) and gas kick detection (Feo et al. (2019)).

DAS has also been used for evaluating the performance of Gas lift (Hemink and Horst (2018), Baciu et al. (2016)), Electrical Submersible Pump (ESP) (Allanic et al. (2013), Williams et al. (2015)), Flow control devices (Xia et al. (2013, 2014, 2015), Banack et al. (2019)), and sand control devices through sand ingress prediction (Mullens et al. (2010), Sadigov et al. (2017), Thiruvenkatanathan et al. (2016)).

Although there are many studies for rate and phase determination, a few works have been published about flow regime determination (Soroush et al. (2019) and Fidaner (2017)).

SAGD Monitoring

Among the published papers, MacPhail et al. (2016) used DAS and DTS to estimate steam breakthrough and Shirdel et al. (2016, 2019) utilized DAS and DTS to analyze steam performance. Obviously, there is not enough research about SAGD monitoring using DAS specially related to flow regime determination. Due to the complexity of flow behavior in SAGD projects, a comprehensive knowledge about existing completion designs and corresponding flow regimes (patterns) are needed to efficiently use DAS and DTS systems in SAGD lab and field tests. As a result, relating the acoustic signals to the flow behavior would be more precise, reliable and easier. Therefore, in the following sections completion designs and corresponding possible flow regimes are discussed and appropriate flow loop designs are proposed for future tests.

SAGD Completion Designs

We used completion designs of SAGD producers in the literature (AER performance presentations, 2019) and categorized the completions into four main groups: standalone screen (SS), scab liner (SL), tubing deployed (TD) and liner deployed (LD) completions. Figure 4 demonstrates examples of each group. As shown in Fig. 4 (a) production is from standalone screen but in Fig. 4 (b) fluid is produced from screen toward toe and then scab liner. In Fig. 4 (c) inflow control devices (ICDs) are installed on tubing, therefore, flow is controlled in every zone. Finally, in Fig. 4 (d) ICDs are installed directly on liners (screens) to control the zonal production.

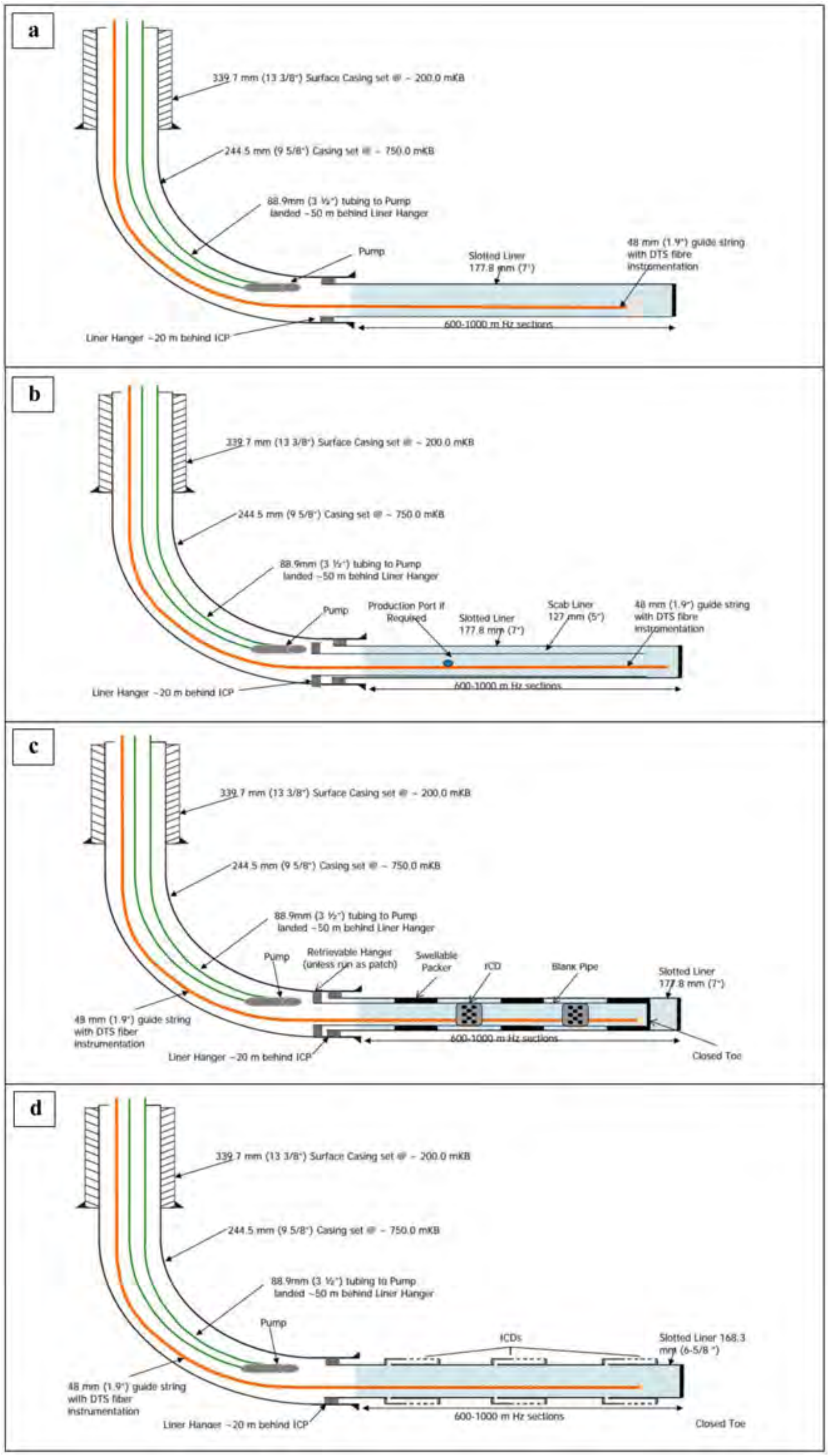

Figure 4—Four groups of completion designs in SAGD operations; (a) SS: standalone screen, (b) SL: scab liner, (c) TD: tubing deployed, and (d) LD: liner deployed (AER performance presentations, 2019)

Each company has used one or more of the designs shown in Fig. 4 in their projects but the screen and tubing dimeters might differ in each project. Table 1 summarizes existing completion designs that companies have used in their SAGD projects and their corresponding screen and tubing diameters. In the following sections, it is shown that completion design as well as sizes of screen and tubing are important factors in flow regime determination.

Table 1—Completion designs in SAGD projects with their corresponding screen and tubing size; SS: standalone screen, SL: scab liner, TD: tubing deployed, LD: liner deployed (AER performance presentations, 2019)

Company	Project	Completion	Screen diameter (inch)	Tubing diameter (inch)
AOC	Hangingstone	SS	8-5/8	-
	Lemister	SS	6-5/8, 7, 8-5/8	-
Cenovus	Christina Lake	SS, SL, TD	7	4-1/2
	Foster Creek	SS, TD	7	4-1/2
CNOOC	Long Lake	SS, SL, TD	7, 8-5/8	4-1/2, 5-1/2
CNRL	Jackfish	SS, SL	8-5/8	3-1/5, 4-1/2
	Kirby South	SS, SL, TD, LD	6-5/8, 7	3-1/2, 4-1/2, 5
	Primrose	SL, TD	7	4-1/2, 5
ConocoPhilips	9426	SL, TD, LD	7, 8-5/8	4-1/2
Harvest	BlackGold	SS	7	-
Husky	Sunrise	SS, SL	9-5/8, 7	5-1/2, 4-1/2
	Tucker Lake	SS	7, 4-1/2	-
JACOS	Hangingstone	SL	7	4-1/2
MEG	Christina Lake	SL, TD	7	3-1/2
Pengrowth	Lindbergh	SL	7	3-1/2, 4-1/2
Suncor	Firebag	SL, TD, LD	8-5/8, 9-5/8	3-1/2, 4-1/2, 5-1/2
	Mackay River	SL, TD	7, 8-5/8, 9-5/8	3-1/2, 4-1/2

Flow Regime Charts

We used literature flow regime charts for pipe (Mandhane et al., 1973) and annulus (Eyo and Lao, 2019) and developed new charts on which the range of SAGD production data such as water cut (WC), gas oil ratio (GOR) and liquid rate were superimposed. Therefore, by knowing these parameters, one can predict flow regime at any stage of production. Figure 5 depicts possible flow regimes that can develop inside the pipe or annulus.

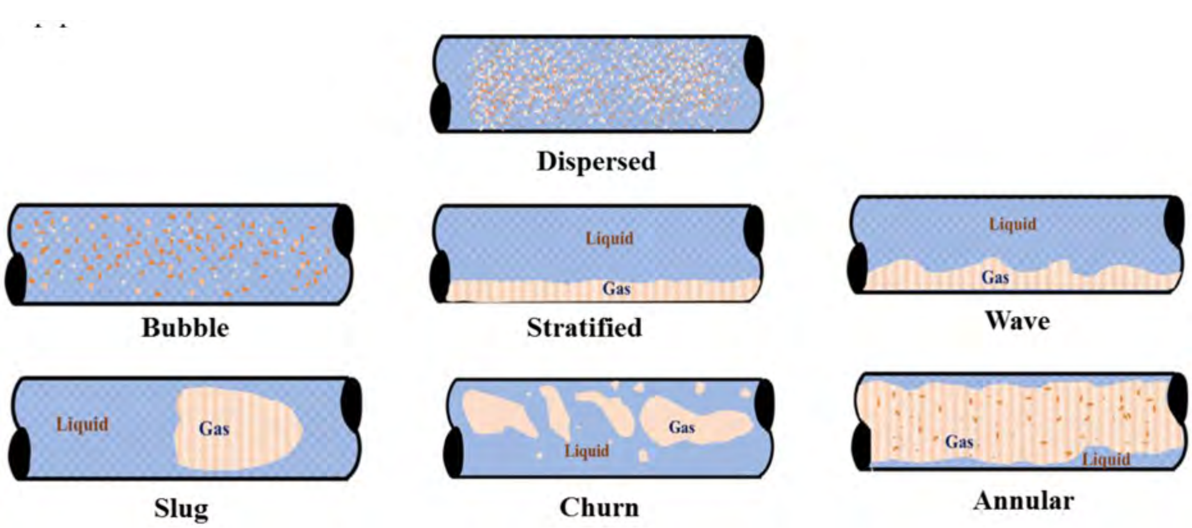

Figure 5—Possible flow regimes that might be formed inside the pipe and annulus.

As it can be observed in Table 1, most popular screen sizes are 7 and 8 5/8 inch and tubing sizes are 4 ½ and 5 ½ inch. Figure 6 shows flow regime chart for 4 ½ tubing and 7 inch annulus. For both tubing and annulus, flow rate was changed from 0 to 6000 bbl/day and two water cuts of 30 and 70% were considered. Apparently, the calculated velocity values at such conditions are smaller than the available flow regime experimental tests in the literature and therefore, the flow regime never reaches slug flow. We obtained a similar conclusion for other tabular sizes. It should be noted that inclusion of steam breakthrough and completion design in the calculations of these charts were not possible. In the following section these factors are included.

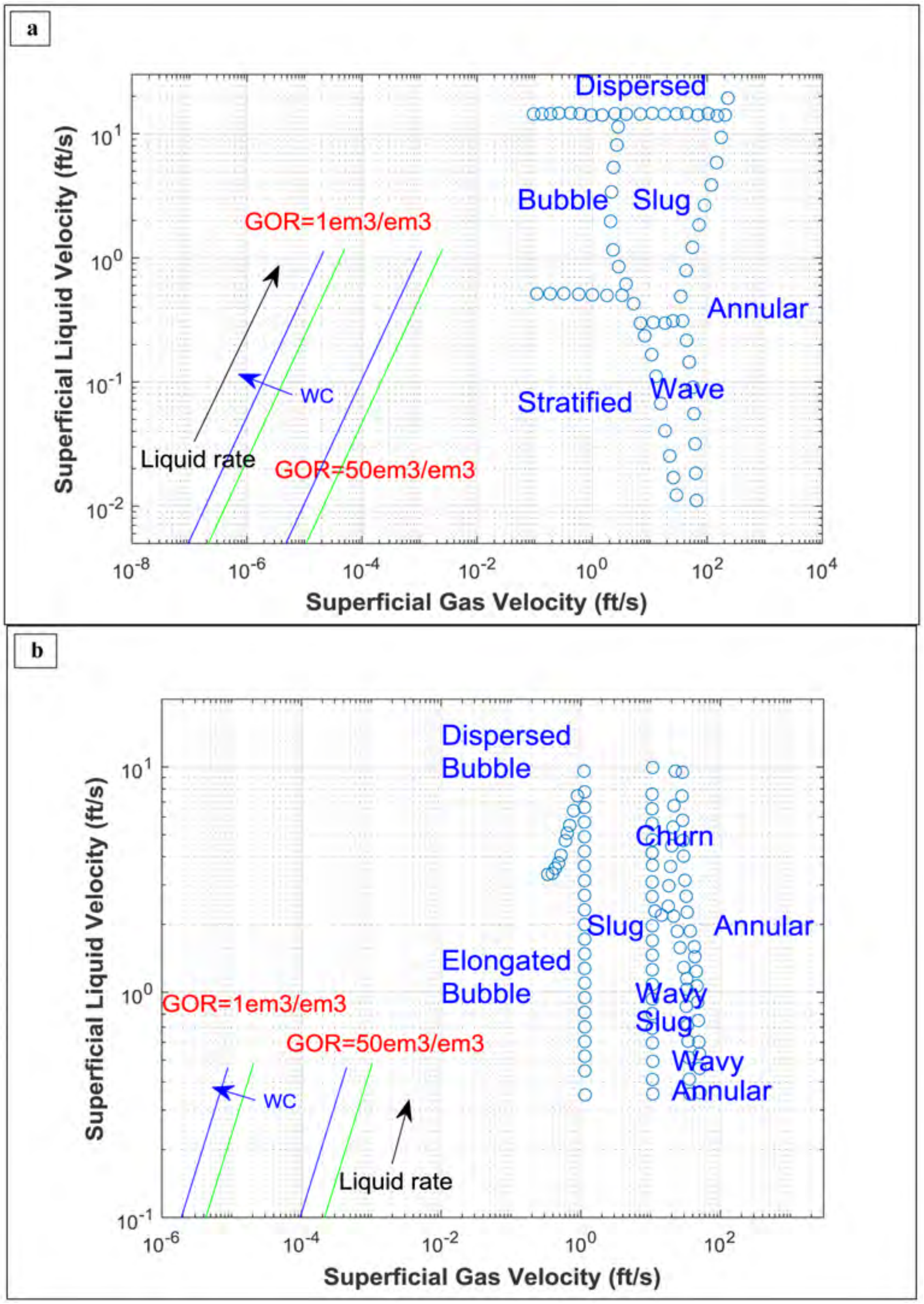

Figure 6—Flow regime charts for tubing size of 4 ½ and annulus size of 7 inch; (a) tubing and (b) annulus

Flow Regime Distribution

To incorporate the effect of completion design and steam breakthrough in flow regime calculations, we plotted flow regimes distribution along the well. We assumed a 1000 m horizontal well and obtained flow regime distribution along the well in two cases (a) no steam breakthrough (b) with steam breakthrough for different completion designs. Three liquid production rates (1000, 3000, 6000 bbl/d), steam injection of 400 m3/d, water cut of 80% and gas oil ratio of 10 em3/em3, temperature of 200ºC and pressure of 2500 kpa were used in the designs.

Standalone screen

Based on the data in Table 1, we selected two main screen diameters: 7 and 8 5/8. Figure 7 shows flow regime distributions for a 1000 m horizontal well with standalone screen design, 7 inch screen diameter in cases of no steam breakthrough and steam breakthrough (at heel, middle and toe). As can be seen in this figure, flow regime is stratified when steam breakthrough does not occur while at breakthrough locations flow regime changes to wavy stratified. We obtained similar distributions for 8 5/8 inch standalone screen. In addition, even when we changed liquid rate from 1000 to 6000 bbl/d, we obtained similar flow regime distribution.

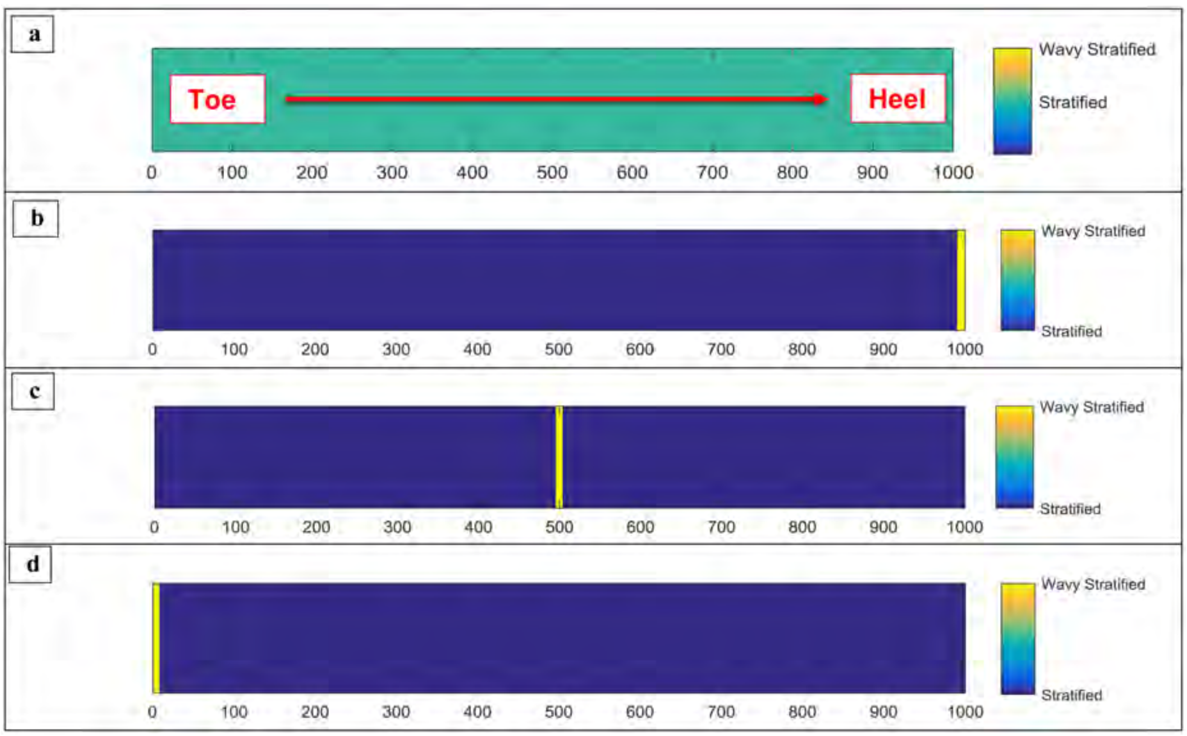

Figure 7—Flow regime along 1000 m well with standalone screen design, 7 inch dimeter standalone screen; (a) no steam breakthrough, (b) steam breakthrough at heel, (c) in the middle and (d) at toe

Scab liner

Figure 8 presents flow regime distributions for a 1000 m horizontal well with scab liner design, 4 ½ inch scab liner and 7 inch screen. Flow regime was evaluated for both annulus (top figure) and tubing (bottom figure) for the case of no steam breakthrough. For both annulus and tubing bubble flow regime was detected. We obtained similar distributions for 5 ½ inch scab liner and 8 5/8 inch screen. In addition, we changed liquid rate from 1000 to 6000 bbl/d but the distributions were comparable.

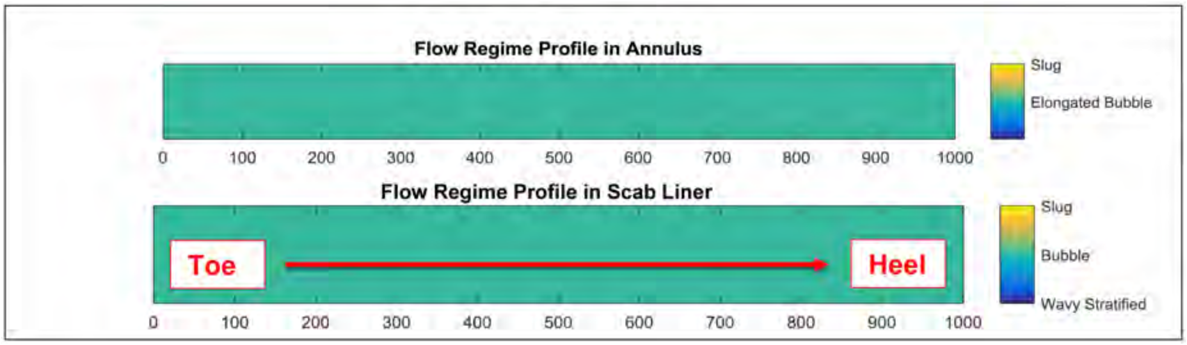

Figure 8—Flow regime along 1000 m well with scab liner design, 4 ½ inch dimeter scab liner and 7 inch screen for no steam breakthrough; top figure is for annulus and bottom figure is for scab liner

Figures 9 to 11 illustrate flow regime distributions in the case of steam breakthrough at the heel, middle and toe. In these figures, (wavy) slug and annular flow in annulus and annular flow in scab liner can be observed at breakthrough locations. We obtained comparable distributions for 5 ½ inch scab liner and 8 5/8 inch screen. In addition, we changed liquid rate from 1000 to 6000 bbl/d and still obtained comparable results.

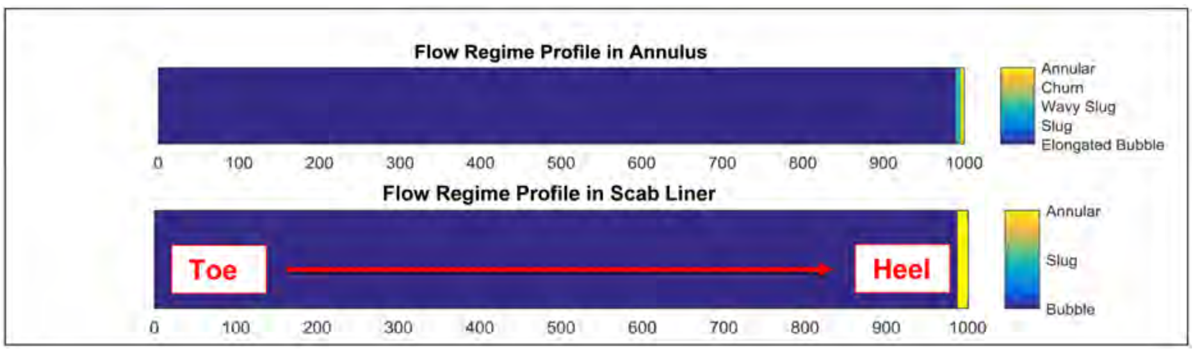

Figure 9—Flow regime along 1000 m well with scab liner design, 4 ½ inch dimeter scab liner and 7 inch screen for steam breakthrough at heel; top figure is for annulus and bottom figure is for scab liner

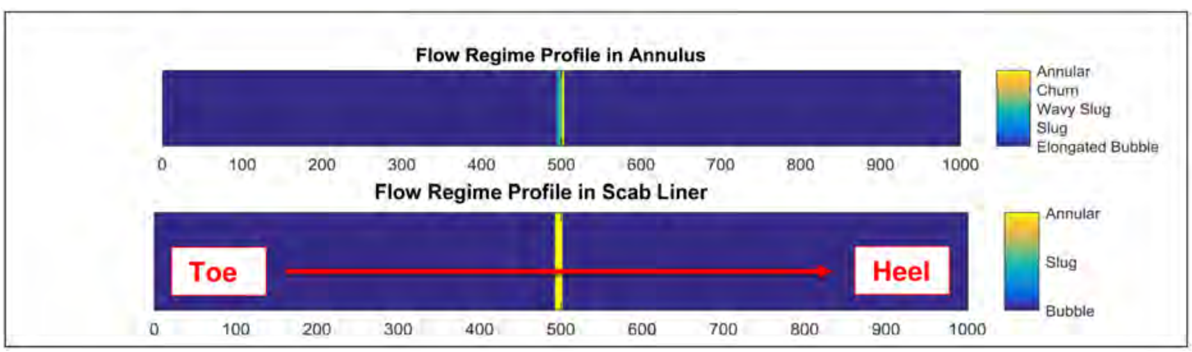

Figure 10—Flow regime along 1000 m well with scab liner design, 4 ½ inch dimeter scab liner and 7 inch screen for steam breakthrough in the middle; top figure is for annulus and bottom figure is for scab liner

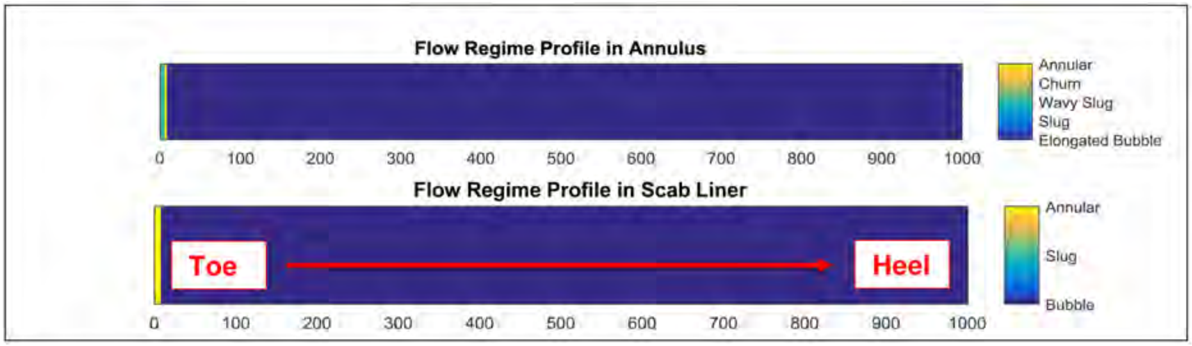

Figure 11—Flow regime along 1000 m well with scab liner design, 4 ½ inch dimeter scab liner and 7 inch screen for steam breakthrough at toe; top figure is for annulus and bottom figure is for scab liner

Tubing deployed

Figure 12 depicts flow regime distributions for a 1000 m horizontal well with tubing deployed completion design, 4 ½ inch tubing and 7 inch screen. Flow regime was evaluated for both annulus (top figure) and tubing (bottom figure) assuming no steam breakthrough occurs. Plots were created for three liquid rates of 1000, 3000 and 6000 bbl/d. It can be seen that flow regime inside the annulus is bubble flow but inside the tubing varies with liquid rate. For example, for 1000 bbl/d liquid rate two flow regimes exist (stratified and bubble) but for 3000 and 6000 bbl/d liquid rate three flow regimes exist (stratified, bubble and dispersed). Comparing liquid rates of 3000 and 6000 bbl/d, higher liquid rate expedites the bubble and disperse flow. We obtained similar trends for 5 ½ inch tubing and 8 5/8 inch screen but bubble and disperse regimes form slower because the tubing size increases.

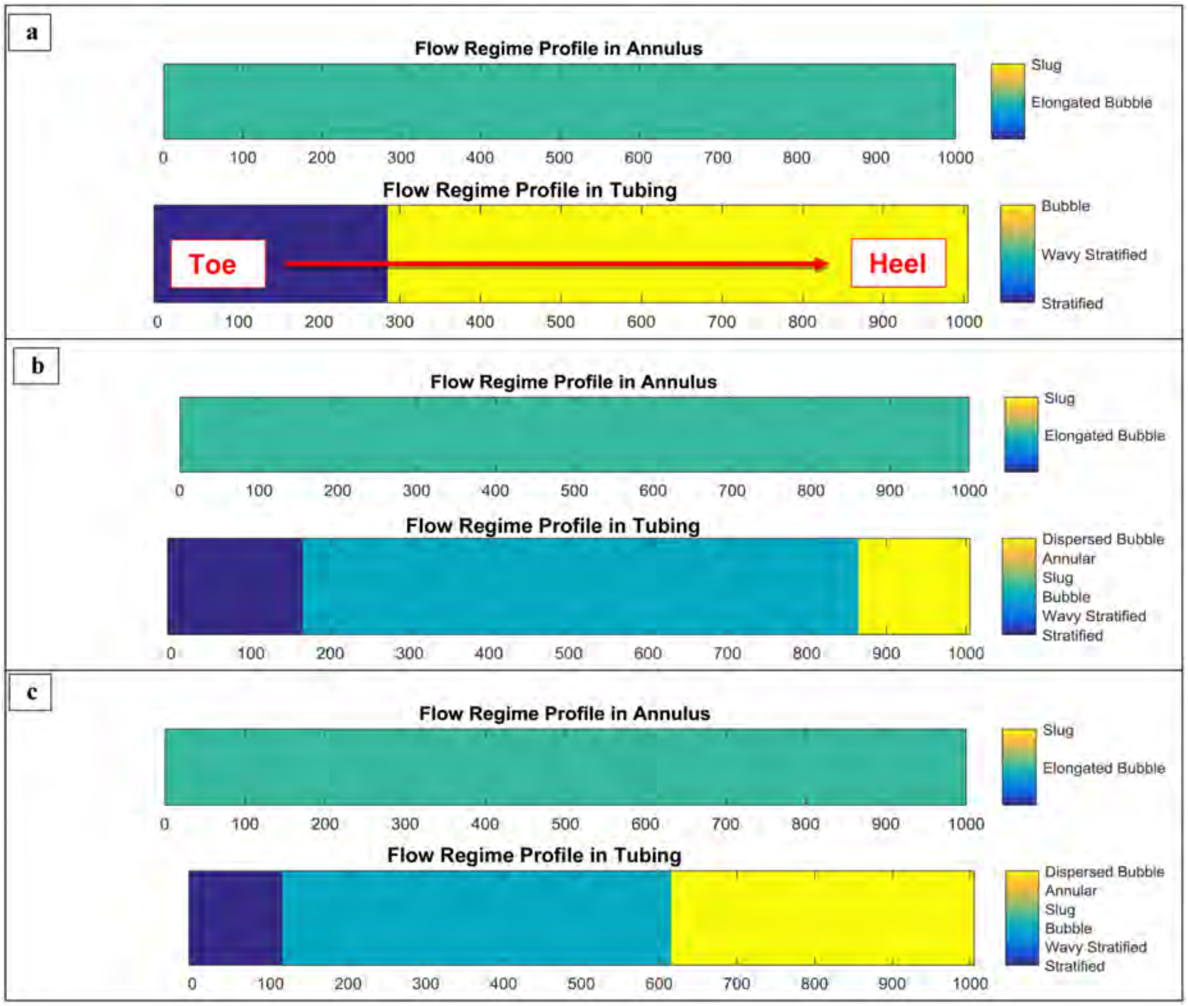

Figure 12—Flow regime along 1000 m well with tubing deployed completion design, 4 ½ inch dimeter tubing and 7 inch screen for no steam breakthrough; top figure is for annulus and bottom figure is for tubing; (a) liquid rate=1000 bbl/d, (b) liquid rate=3000 bbl/d, (c) liquid rate=6000 bbl/d

Figure 13 shows flow regime distributions for the same completion design with steam breakthrough happening at the heel. It can be seen that flow regime inside the annulus is wavy slug/annular at breakthrough location and bubble flow at other locations. However, inside the tubing, three flow regimes exist (stratified, bubble and annular for 1000 bbl/d liquid rate while stratified, bubble and dispersed for 3000 and 6000 bbl/d liquid rate). Again for 5 ½ inch tubing and 8 5/8 inch screen similar trends were observed but bubble and disperse regimes form slower since the tubing size increases.

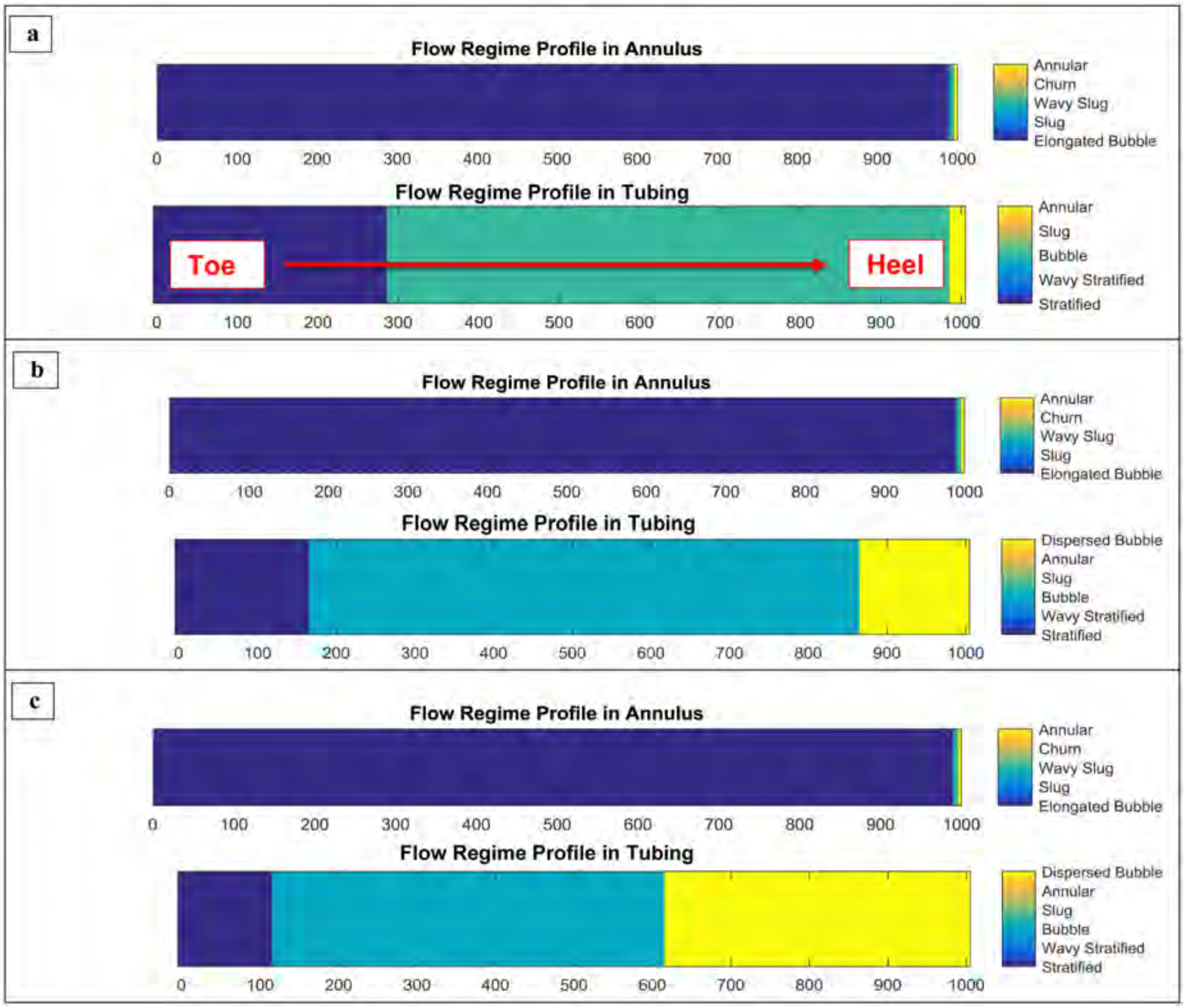

Figure 13—Flow regime along 1000 m well with tubing deployed completion design, 4 ½ inch dimeter tubing and 7 inch screen for steam breakthrough at heel; top figure is for annulus and bottom figure is for tubing; (a) liquid rate=1000 bbl/d, (b) liquid rate=3000 bbl/d, (c) liquid rate=6000 bbl/d

Figure 14 shows flow regime distributions for the same completion design if steam breakthrough occurs in the middle part of the horizontal well. Similarly, flow regime inside the annulus is wavy slug/annular at breakthrough location and bubble flow at other locations. Inside the tubing three flow regimes exist (stratified, bubble and annular for 1000 bbl/d liquid rate while stratified, bubble and dispersed for 3000 and 6000 bbl/d liquid rate). Similarly, for 5 ½ inch tubing and 8 5/8 inch screen comparable trends were observed but bubble and disperse regimes form slower since the tubing size increases.

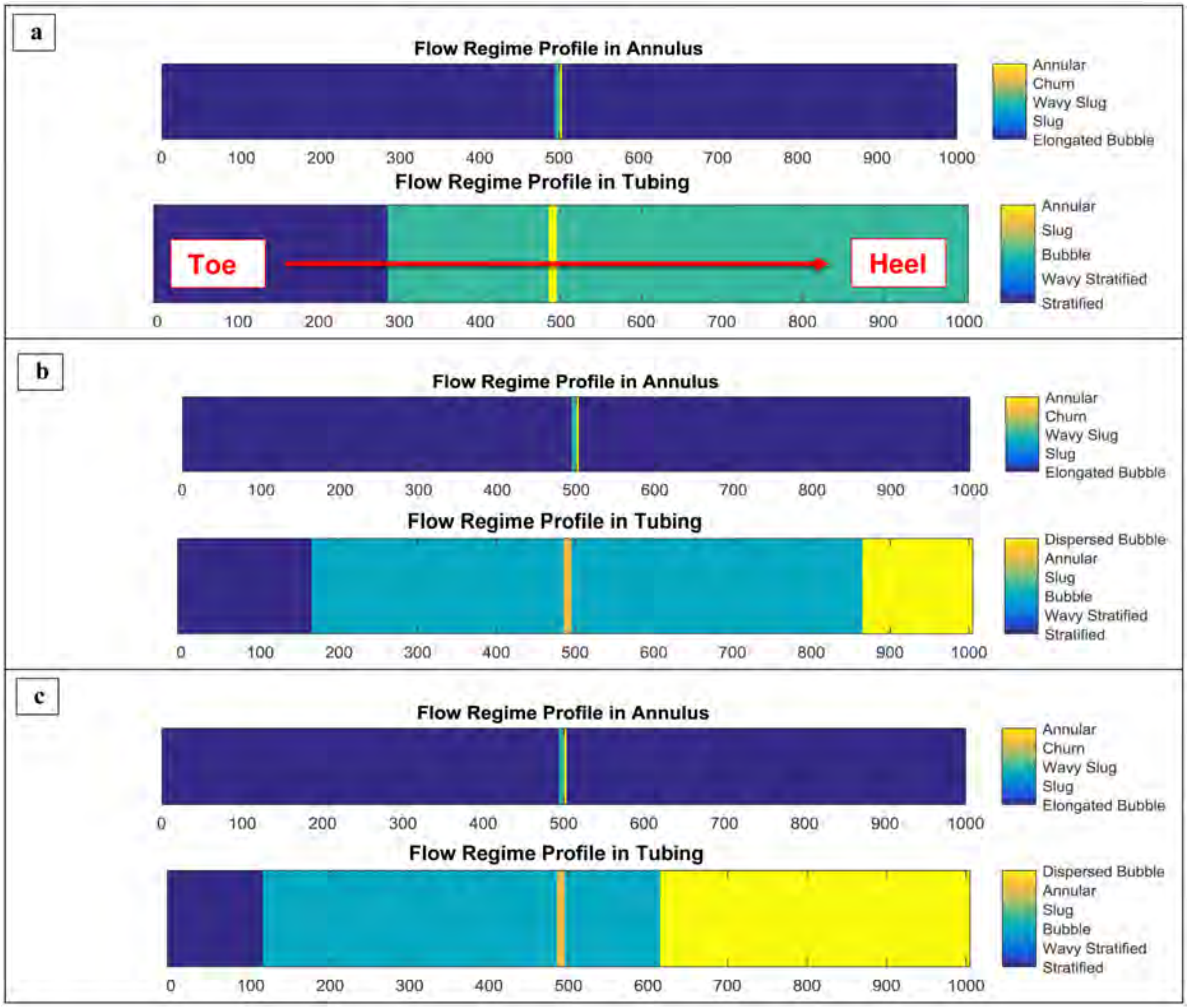

Figure 14—Flow regime along 1000 m well with tubing deployed completion completion, 4 ½ inch dimeter tubing and 7 inch screen for steam breakthrough in the middle; top figure is for annulus and bottom figure is for tubing; (a) liquid rate=1000 bbl/d, (b) liquid rate=3000 bbl/d, (c) liquid rate=6000 bbl/d

Figure 15 shows flow regime distributions for the same completion design if steam breakthrough occurs at the toe. Similarly, flow regime inside the annulus is wavy slug/annular at breakthrough location and bubble flow at other locations. For 1000 bbl/d liquid rate three flow regimes exist inside the tubing (stratified, bubble and annular) but for 3000 and 6000 bbl/d liquid rate four flow regimes exist (stratified, bubble, annular and dispersed). Similarly, for 5 ½ inch tubing and 8 5/8 inch screen comparable trends were observed but bubble and disperse regimes form slower since the tubing size increases

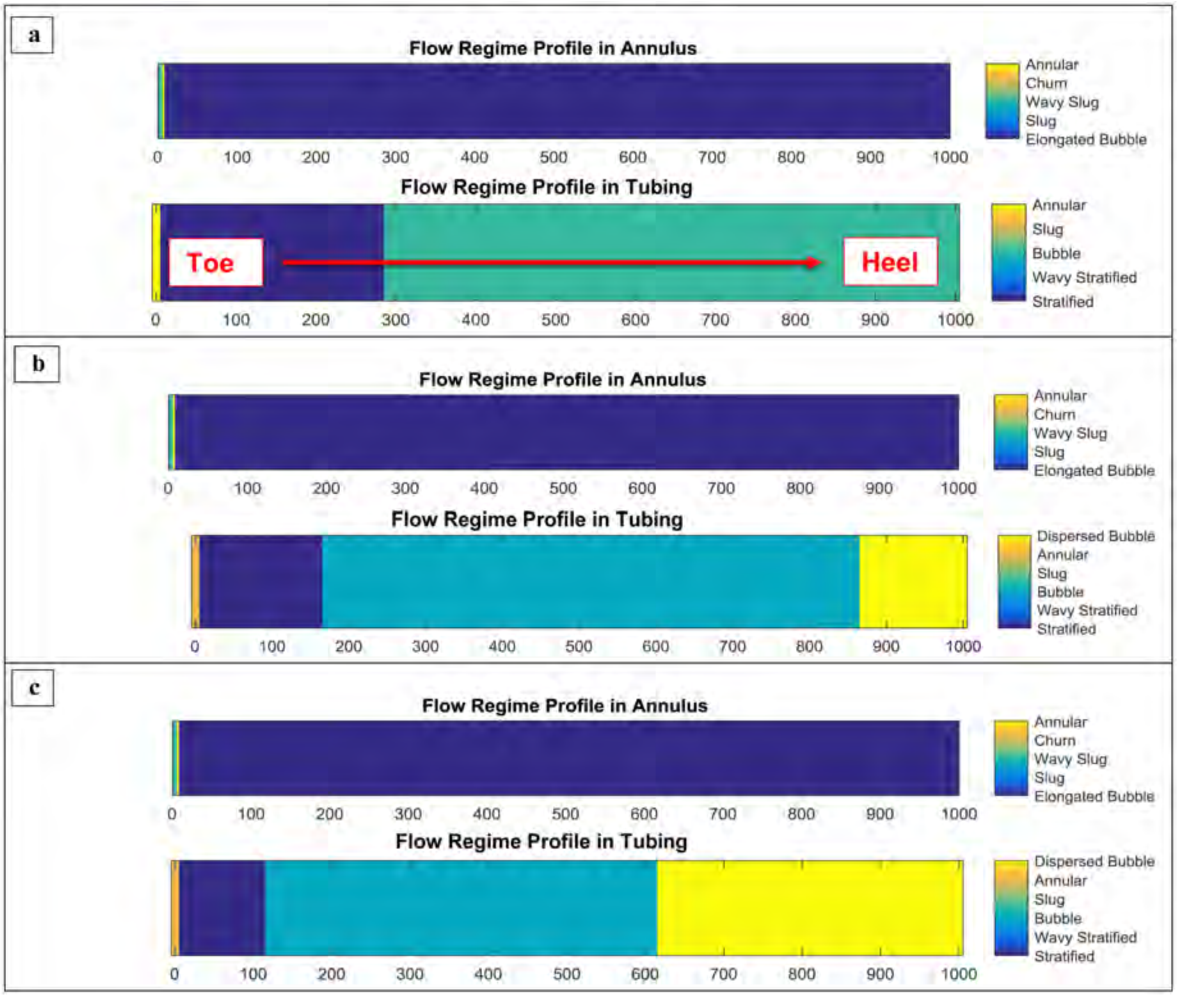

Figure 15—Flow regime along 1000 m well with tubing deployed completion completion, 4 ½ inch dimeter tubing and 7 inch screen for steam breakthrough at toe; top figure is for annulus and bottom figure is for tubing; (a) liquid rate=1000 bbl/d, (b) liquid rate=3000 bbl/d, (c) liquid rate=6000 bbl/d

Liner deployed

Figure 16 presents flow regime distributions for a 1000 m horizontal well with liner deployed completion design which includes a 7 inch screen. Flow regime was evaluated for the case of no steam breakthrough at three liquid rates of 1000, 3000 and 6000 bbl/d. It can be seen that two flow regimes exist (stratified and bubble) for 1000 and 3000 bbl/d liquid rate while three flow regimes exist (stratified, bubble and dispersed) for 6000 bbl/d liquid rate. We obtained similar trends assuming 8 5/8 inch screen but bubble and dispersed form slower.

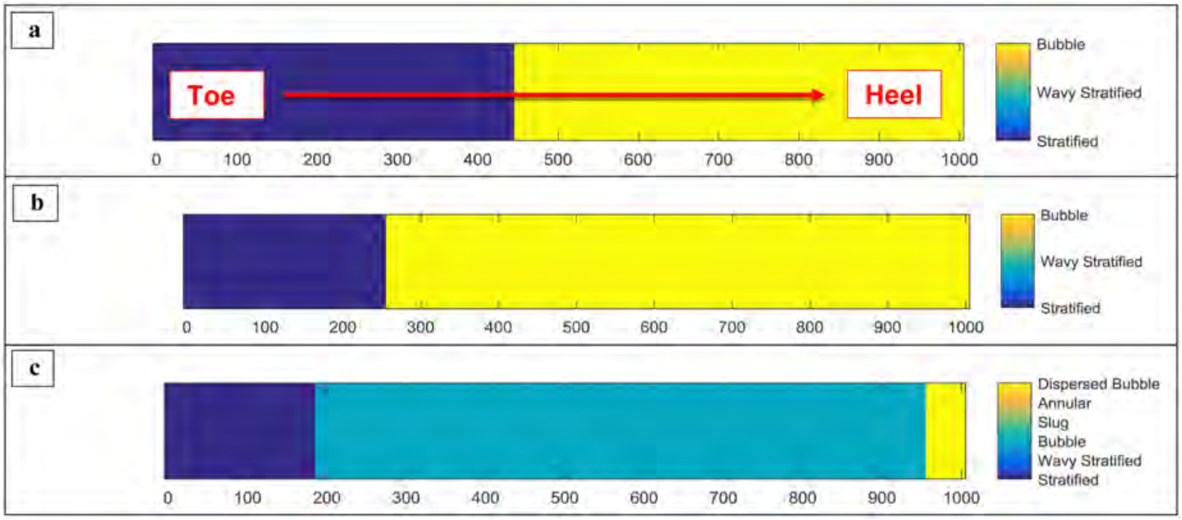

Figure 16—Flow regime along 1000 m well with liner deployed completion design, 7 inch dimeter screen with no steam breakthrough; (a) liquid rate=1000 bbl/d, (b) liquid rate=3000 bbl/d, (c) liquid rate=6000 bbl/d

Figure 17 presents flow regime distributions for the same completion design with steam breakthrough at heel. It can be seen that in this condition three flow regimes exist (stratified, bubble and slug for 1000 and 3000 bbl/d liquid rate while stratified, bubble and dispersed for 6000 bbl/d liquid rate). We obtained comparable trends assuming 8 5/8 inch screen but bubble and dispersed form slower.

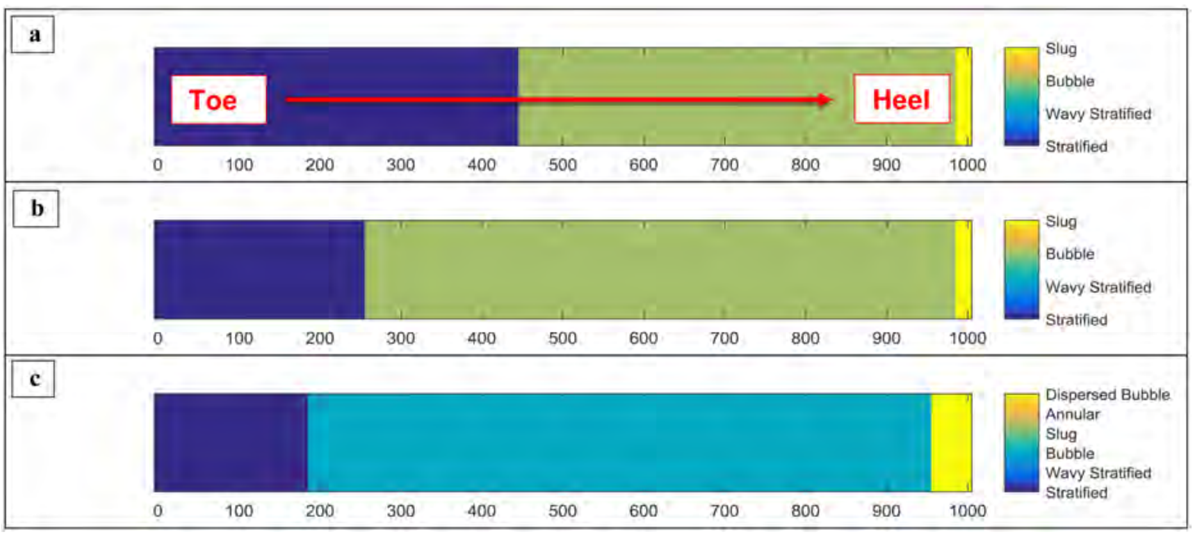

Figure 17—Flow regime along 1000 m well with liner deployed completion design, 7 inch dimeter screen with steam breakthrough at heel; (a) liquid rate=1000 bbl/d, (b) liquid rate=3000 bbl/d, (c) liquid rate=6000 bbl/d

Figure 18 presents flow regime distributions for the same completion design with steam breakthrough happening in the middle of horizontal section of the well. Similarly, it can be realized that three flow regimes exist (stratified, bubble and slug for 1000 and 3000 bbl/d liquid rate while stratified, bubble and dispersed for 6000 bbl/d liquid rate). Similarly, we obtained comparable trends assuming 8 5/8 inch screen but bubble and dispersed form slower.

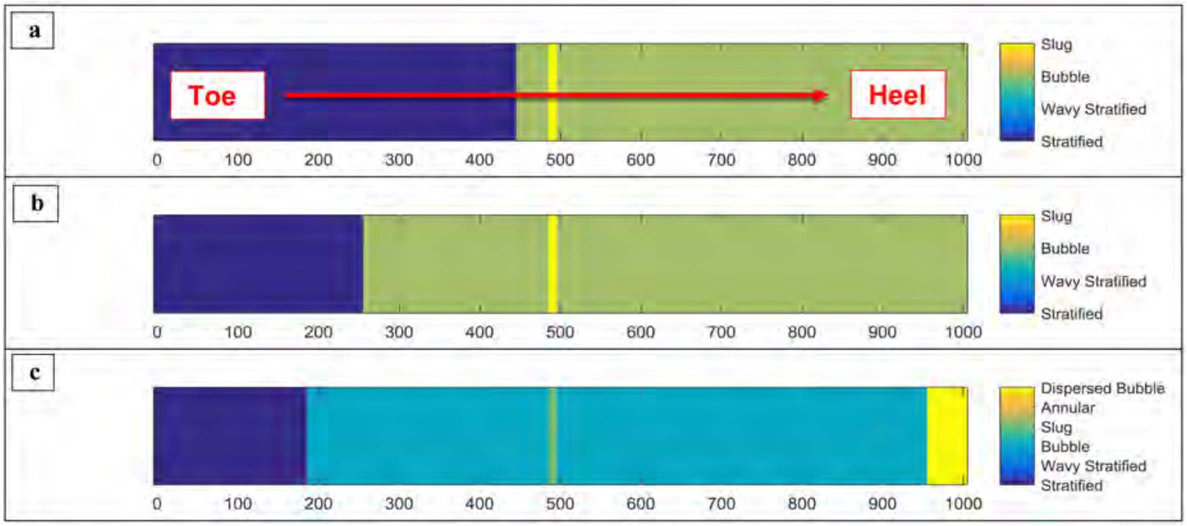

Figure 18—Flow regime along 1000 m well with liner deployed completion design, 7 inch dimeter screen with steam breakthrough in the middle; (a) liquid rate=1000 bbl/d, (b) liquid rate=3000 bbl/d, (c) liquid rate=6000 bbl/d

Figure 19 presents flow regime distributions for the same completion design with steam breakthrough occurring at the toe. It can be realized that three flow regimes exist (stratified, wavy stratified and bubble for 1000 and 3000 bbl/d liquid rate while stratified, bubble and dispersed for 6000 bbl/d liquid rate). Similarly, we obtained comparable trends assuming 8 5/8 inch screen but bubble and dispersed form slower. It should be noted that for all of these designs, gas oil ratio and water cut had lower impact on flow regime distribution relative to liquid rate.

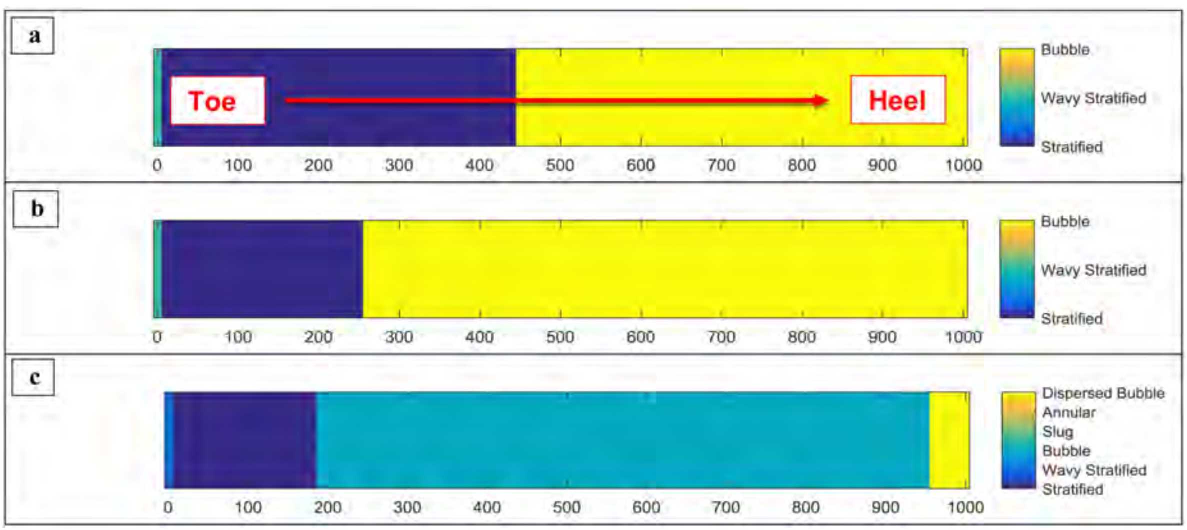

Figure 19—Flow regime along 1000 m well with liner deployed completion design, 7 inch dimeter screen with steam breakthrough at toe; (a) liquid rate=1000 bbl/d, (b) liquid rate=3000 bbl/d, (c) liquid rate=6000 bbl/d

Flow Loop Designs

Eventually, based on completion designs discussed previously and their importance on flow regime and flow profiling, we proposed four flow loop designs for DAS lab testing (Fig. 20–23). For standalone, tubing deployed and liner deployed completions, one fiber cable was installed in the setup. For scab liner completion, two fiber cables were deployed: one in annulus and one in tubing.

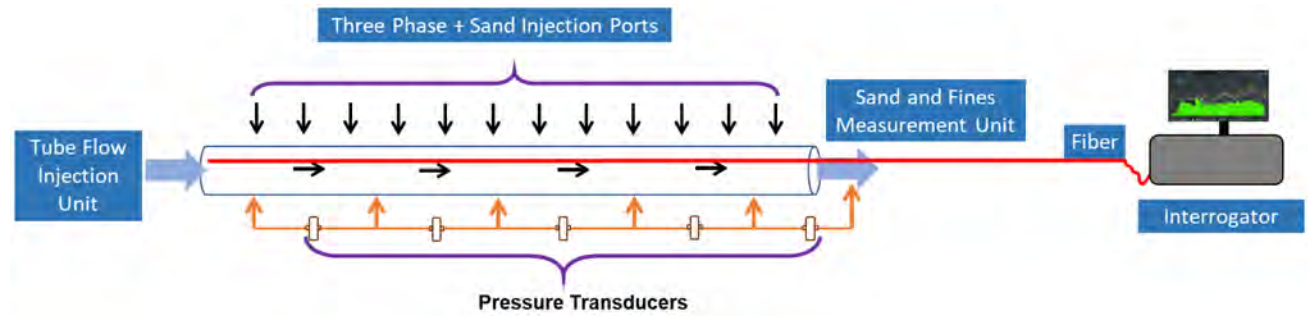

Figure 20—Design 1: standalone screen completion

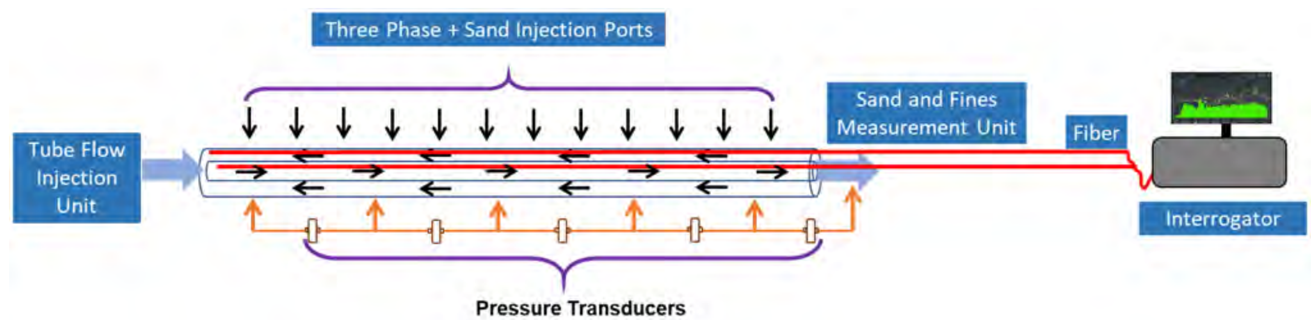

Figure 21—Design 2: scab liner completion

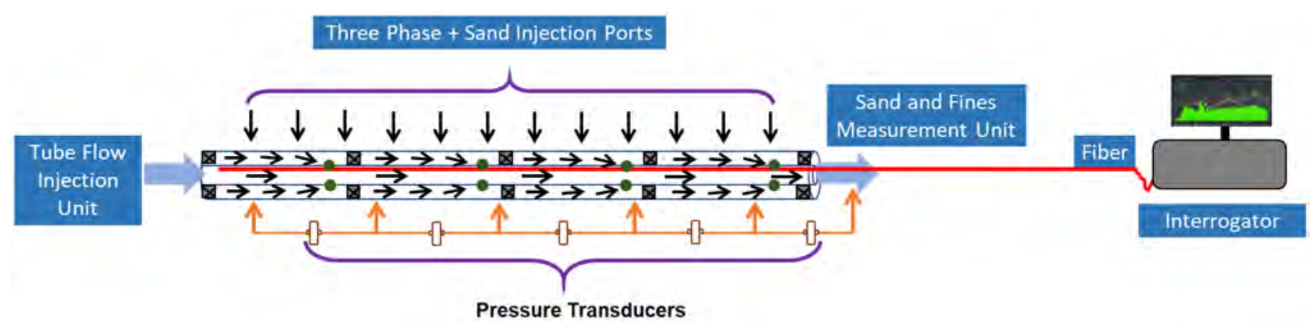

Figure 22—Design 3: tubing deployed completion

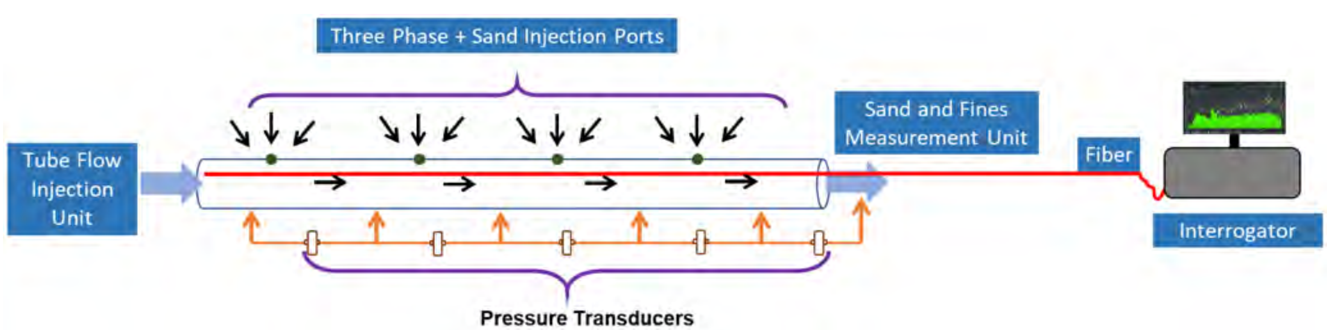

Figure 23—Design 4: liner deployed completion

Summary and Conclusions

This work has been presented in two sections, the first section presented a review of DAS publications while the second part discussed SAGD completion designs and corresponding possible flow regimes. The following summary and conclusions were obtained in this study:

1. DAS systems have been applied in oil and gas industry for two decades in the areas of seismic, hydraulic fracturing, well integrity and flow profiling.
2. In most cases, DAS recordings are comparable but cost effective with low risk of environmental issues. DAS recordings have high resolution along the well and real time measurements.
3. DAS systems have been deployed for SAGD projects to determine steam breakthrough and flow profiling. There are a few publications about the application of DAS on SAGD monitoring specially flow regime determination.
4. Completion designs affect flow regime and DAS recordings. Therefore, knowing the distribution of flow regime helps to correlate DAS data to flow data. It is important that flow regime be determined prior to DAS deployment.
5. Flow regime variation highly depends on completion design, the occurrence of steam breakthrough and its location and liquid rate.
6. Smaller tubing diameter expedite the occurrence of bubble, slug or disperse flow.
7. Existence of control device (for example for the case of tubing deployed and liner deployed) changes the flow regime toward slug, annular and dispersed flow.
8. In most of the cases, annular or slug flow occurs at steam breakthrough locations.
9. Based on the lessons in this study, four flow loop designs were proposed for future DAS lab tests.

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