The Effect of Screen Aperture Size on Fines Production and Migration in SAGD Production Wells

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The Effect of Slot Width and Density on Fines Migration and Production in SAGD Operations

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ABSTRACT

The quantification of fines migration in the vicinity of sand control screens in SAGD wells is of paramount importance to operating companies, who require the wells to operate under optimum conditions for a period of 10-15 years. Fines migration can lead to the plugging of pore spaces around the liner and result in reduced permeability in the liner's vicinity, hence, lowering the wellbore productivity.

This paper investigates the fines migration in relation to slot width and density in SAGD wells. A series of laboratory experiments was performed by using a Sand Retention Testing (SRT) facility which accommodates a sand pack sample and a multi-slot coupon to represent the near-wellbore high-porosity zone and sand control liner, respectively.

As fluid was pumped through the sand pack and across the slotted coupon, the pressure drop across the sand pack and coupon was measured, along with the mass and Particle Size Distribution (PSD) of produced fines and sand. After the flow test, the sand pack was dissected, and the PSD of fines portion of sand pack was measured to assess the movement and concentration of fines over the course of the test.

Test observations indicate that the slot width, slot density, and the flow rate highly affect the fines migration/production and the PSD of the migrated and produced fines. Larger slot widths increase the mass of the produced and migrated fines. Further observations indicate that the mass and size of produced fines is highly dependent on the flow rate and that there is a critical rate below which little amounts of fines are produced or move in the porous medium.

KEY WORDS

Fines migration, Sand Retention Test (SRT), Particle Size Distribution (PSD), Clay content, Sand Control, SAGD.

INTRODUCTION

Slotted liners and Wire-wrapped Screens (WWSs) are widely used as Sand Control Device (SCD) for SAGD operations. These devices are designed to (1) control the sand flow into the horizontal well, (2) discharge the mobilized fines (<44 μm), and (3) provide the required path for fluid flow (hot bitumen and water).

In many cases, although SCDs successfully halt the production of sand, they are not successful in preventing severe plugging and the ensuing increase in the pressure drop between the injector and producer wells (Williamson et al., 2016). This high pressure drop can be due to the plugging of the pore in the near screen area and/or screen plugging. The screen plugging can be compounded with liner corrosion, chemical scaling, fines migration, water breakthrough, water production, asphaltene precipitation, silica scaling and clay scaling (Schulien et al., 1997; Bennion et al., 2008; Goodman et al., 2010; Romanova and Ma, 2013; Fermaniuk et al., 2015). To understand how fines migration affects the screen performance, we need to understand the fines mobilization, transport, and capture.

De Zwart (2007) identified two conditions for fines mobilization in porous media: (1) presence of the fines which is determined by the lithological conditions, and (2) certain chemical and hydrodynamic local conditions, which let the particles enter and remain in suspension. In addition to the presence of the existing fines due to the lithological condition, further fines could be generated via in-situ precipitation of supersaturated mineral phases (De Zwart, 2007) and thermal mineral diagenesis (Williamson et al., 2016).

Certain chemical and physical conditions influence the mobilization and transport of the fines (Valdes, 2002; De Zwart, 2007; Mahmoudi et al., 2016b). For large particles (>10µm), hydraulic drag forces are the dominant grain removal mechanism. For smaller particles (<1 µm), electro-kinetic forces are the dominant forces (De Zwart, 2007). Particles between 1 and 10 µm are subjected to different forces controlling their mobilization and transport.

The transport of the fines is related to the pore throat size distribution within the sample, fluid chemistry, distribution of the fines in the pore structure, and hydrodynamic conditions (De Zwart, 2007). The mobilized fines can be transported by the fluid flow through the pore space leading to the entrapment and clogging by hydrodynamic bridging, sedimentation, and interception (Valdes, 2002).

The average pore diameter, pore throat size, ratio of the pore body to the pore-throat size, and the ratio of pore throat size to mobilized fines size are of significant importance in fines transport and entrapment. There are several experimental/ analytical methods (Kovacs, 1981; Pittman, 1992, 2001; Uno et al., 1998; Nabawy et al., 2009; Blunt et al., 2013; Mukunoki et al., 2016) and heuristic rule of thumbs (Coberly, 1937; Harris and Odom, 1982) to predict the average pore/pore throat size based on PSD, permeability and porosity. Using these correlations, bridging theory and the impairment rule, one could get an estimate of the size of the particles which could plug the pores. Experimental work (Barkman and Davidson, 1972; Abrams, 1977; Van Oort et al., 1993) concluded that:

1. Particles equal or larger than one-third of the average pore throat size, bridge at the entrance of pore throat.
2. Particles smaller than one-third but larger than one-seventh of the average pore throat size deposit in the pore and cause the reduction in effective pore/pore throat size.
3. In slow flow rates, where the gravitational force is considerable for the small particle compared to the drag force, particles smaller than one-seventh but larger than one-fourteenth of the average pore size deposit in the pore and cause the reduction in effective pore/pore throat size.
4. Particles that are smaller than one-fourteenth of the pore throat size pass through the pores with minor or no impairments.

The fines concentration and distribution in the flow stream are controlled by the velocity (hydrodynamic forces/drag forces) and the direction of the flow (De Zwart, 2007). Field observations by Prins (2003) also indicated the dependency of pore plugging in near wellbore region to fluid velocities. In the near wellbore region, due to the flow convergence, fluid velocity is high and the streamline is changed due to the convergence of flow toward the screen. The effect of this acceleration of the flow towards the screen and change in the flow path is more significant in higher flow rate. Kaiser et al. (2000) concluded that the convergence and drag forces in the vicinity of slotted liners are related to the flow rate, size, and spacing of the slots.

Regarding the effect of the slot size and density on local fluid velocity close to the screen and fines migration, one would expect that the slot size and density selection could affect to the plugging tendency of the screen (Mahmoudi et al., 2016a). Flow performance of the screen could be reduced due to the fines capture and precipitation in pore/pore throats or within the slots.

In this study, we use the pre-packed Sand Retention Test (SRT) facility developed by Mahmoudi et al. (2016b) to investigate the effect of slot width and slot density on the produced fines concentration and size. Also, we studied the changes in fines concentration and size across the sand pack via the post-mortem analysis.

EXPERIMENTAL TESTING

We used the testing procedure and set up developed by Mahmoudi et al. (2016b). The experimental set-up, testing materials and test matrix for this investigation are discussed herein.

EXPERIMENTAL SETUP

We used a pre-pack Sand Retention Testing (SRT) facility which uses multi-slot coupons of the slotted liner. The use of multi-slot versus single-slot coupons that have been conventionally used in the past is considered to be a major improvement over the past research works. The testing matrix is designed to allow the study the effect of slot density and slot width on fines migration and production (**Fig. 1**). The sand pack sample is 6” in diameter and 13” in height.

The experimental setup includes the following components (**Fig. 2**):

1. Fluid injection unit consisting of a diaphragm pump to inject brine at the rate and pressure of 7.6 L/hr and 50 psi, respectively. Rota meters are used to adjust the flow rate.
2. SRT cell (6” in diameter, 13” in height) and porous stones on top of the sample to provide a homogenous fluid flow regime across the sand pack. The multi-slot coupon is placed at the bottom of the sand pack.
3. Sand and fines measurement units consisting of a sand trap that captures the produced sand and silt and a tube for sampling the produced fluid. The mass of the produced fines (particles smaller than 44 μm) is measured based on the turbidity of the produced fluid samples. In addition, the PSD of produced fines is measured by particle size analyzer.
4. Backpressure unit that provides a minor back pressure and the required route for the effluent.

TESTING PROCEDURE

The experiments use synthetized sand packs which are prepared by mixing different proportions of commercial coarse, medium, and fine sand as well as silt and clays (Kaolinite and Illite). The sand pack PSD follows the PSD of DC-II and DC-III oil sands as presented by Abram and Cain (2014) (**Fig. 3**). The commercial sands used in the testing possess similar shape factors (sphericity, angularity and aspect ratio) compared to the natural oil sand grains. Based on image analysis and mechanical testing, Mahmoudi et al. (2015) concluded that duplicated sand packs with similar PSD, grain shape, and mineralogy to the oil sands present similar mechanical properties to those of the oil sands.

SAND PACK PREPARATION

The sand pack synthesis starts with mixing the dry components for 20 minutes to obtain a uniform mixture. Next, brine is added to the mix by as much as 10% dry sand pack weight and is mixed for 10 minutes to obtain a mix with uniform water content.

A moist tamping method similar to the procedure suggested by Ladd (1978) was used to prepare the sand pack. The sand pack is compacted in layers. This procedure leads naturally to samples with different initial porosity and permeability for DC-II and DC-III (**Table 1**).

SAMPLE SATURATION

Due to the initial brine content, the sand pack samples come with an initial water saturation of 78.5% and 71.3% for DC-II and DC-III, respectively. An additional amount of brine is flown from the bottom to the top of the sand pack at a slow rate of 250 ml/hr to fully saturate the sample. The high permeability of the sand packs facilitates the full saturation. The cell is then connected to the pump to establish a low flow rate from the top to the bottom of the sand pack. Pressure transducers are connected to their respective ports along the sand pack.

The brine in these tests contained 0.7% by weight of NaCl and had a pH value of 7.9. The brine was prepared by adding NaCl to demineralized water and mixing thoroughly to obtain a uniform solution. The pH was adjusted by Sodium Bisulphate ($NaHSO4$) as pH booster. The pH and salinity of the brine were chosen based on the average values reported for produced brines in several SAGD projects (Mahmoudi et al., 2016b). Using a monovalent salt (e.g., NaCl) seems to be the extreme case for clay mobilization (Mahmoudi et al., 2016b).

STEP RATE FLUID FLOW INJECTION

Considering a typical SAGD production rate of 1500 bbl/day, one can calculate a reasonable flow rate for the experiments by dividing the field rate by the wellbore length (typically 800m). Typical slotted liners in SAGD wells have 1-3% of Open to Flow Area (OFA). Considering 0.010” for the slot width at the lowest OFA and 7” liner, results in about 200 slots per foot for the slot density. Assuming uniform flow among all slots, one can calculate a flow rate per slot of 10-30 ml/hr. However, some slots may be plugged over time resulting in larger flow rates in unplugged slots. Considering 95% of the slots are plugged, the upper bound for the flow rate for each slot amounts to nearly 600 ml/hr. Accordingly, each test consisted of step-rate injection at seven different flow rates in the range of 0.30 to 2.19 bbl/day, each for 30 minutes. Injected flow rates, depending on the slot density, are equal to about 60 to 540 ml/hr/slot.

Fluid flow rate steps are kept constant for all tests and both PSDs (DC-II and DC-II). However, the different porosity for different PSDs results in different values for the pore volume brine injected (**Fig. 4**).

TEST MATRIX

The test matrix included different multi-slot coupons with slot densities of 30, 42 and 54 Slot per Column (SPC) (**Fig. 5**) and slot width ranging from 0.010” to 0.032”. These slot widths cover the range obtained from the design criteria of 2D70 to 3.5D50 proposed by Fermaniuk (2013) and D10 to 2.0D10 proposed by Coberly (1937) and Suman (1985).

POSTMORTEM ANALYSIS

Each test was followed by post-mortem studies to characterize the slot and pore throat plugging as well as to track the fines mobilization and transport across the sand pack. A 0.5” tube was used to extract three cores from the entire height of the sand pack after the testing completion. From each of these cores, three samples were taken from the top, middle, and bottom (adjacent the coupon) of the cores. Using the wet sieving method, the fine portion (less than 44 µm) of each sample was separated and weighed and the rest of the sample was dried in the oven for 24 hr. The weight of the fine-less portion was used to calculate the fines concentrations for the top, middle, and bottom of each sand pack sample. The comparison of fines concentration before and after the testing allows the assessment of fines migration in the sample during the testing

RESULTS AND DISCUSSION

Pressure measurements indicate negligible pressure drops across the coupon (less than 0.01 psi) for the duration of testing. Post-test inspections indicated no plugging or scaling in the slots, which is consistent with the low pressure drops. Therefore, in this section, we focus on the changes in the concentration of fines (<44µm) close to the slotted liner coupons, and the concentration and size of the produced fines.

Our findings indicate that slot width and slot density influence the fines migration. **Figures 6** and **7** show the fines concentration above the screen and the concentration and PSD of the produced fines in the outflow for DC-III and DC-II, respectively. Lower porosity and permeability of DC-II in comparison to DC-III suggest smaller average pore size for DC-II (see **Table 1**), which makes it more prone to pore plugging by fines than DC-III. In addition, for the same fluid flow rate, the pore-scale flow velocities in DC-II are higher than the pore-scale velocities for DC-III. Higher pore-scale flow velocities facilitate the fines migration.

Figures 6(a) and **7(a)** show the fines concentration above the screen versus slot density for different slot widths. The figures indicate lower fines concentration above the screen for higher slot density at constant slot width. The figures also show drastically lower fines concentration above the screen for wider slots. The comparison of **Figs. 6(a)** and **7(a)** indicates higher fines accumulation (plugging) near the coupon for DC-II which is finer-grained sands with higher fines content compared to DC-III.

Figures 6(b) and **7(b)** show the near-screen fines concentration versus slot width for different slot densities. The figures indicate a decreasing trend in the near-screen fines concentration for higher slot widths. It is interesting to note that the fines content for wider slots approaches the original fines concentration in the sand pack. This suggests the benefit of using the widest slot size that can still keep the sanding within tolerance in reducing the plugging potential.

Figures 6(c) and **7(c)** show the cumulative fines production at the end of the tests versus slot density. Results show higher cumulative fines production for wider slots. Massive solid production (fines and sands) are expected if the slot width exceeds a certain threshold. Cumulative fines production decreases with increase in the slot density, which can be attributed to the lower flow velocity at the constant flow rate and constant slot width but higher slot density.

Figures 6(d) and **7(d)** show the cumulative fines production at the end of the test versus slot width. The figures show higher cumulative fines production for larger slot widths at constant slot density. Further, the cumulative fines production shows a decreasing trend for higher slot density and constant slot width.

Figures 6(e)-6(g) and **7(e)-7(g)** show the fines production, in each fluid flow rate step, for different slot widths at constant slot densities. For lower flow rates, results indicate only slightly higher fines production for higher flow rates. Increasing the flow rate beyond a certain level, however, results in a drastically higher fines production. The figures also indicate higher fines production for wider slots for a given slot density. Based on these results, one can expect plugging of slots may increase the flow rates in adjacent open slots, which in turn may lead to higher rate of fines production and fines movements toward that open slots.

Figures 6(i)-6(j) and **7(i)-7(j)** show the median size of produced fines versus the fluid flow rate for different slot widths at constant slot density. The figures indicate larger median size (D50) of the produced fines for higher flow rates. In particular, increasing the flow rates beyond certain thresholds results in a more drastic increase of the D50, especially, for larger slot widths.

Figures 6(k) and **7(k)** show the median size of the produced fines versus flow rate for different tested coupons. As expected, stronger drag forces in the vicinity of the screen increase the median size of the produced fines. Therefore, for a constant slot width, D50 shows a decrease for higher slot densities at constant flow rate, because of the lower flow velocities and weaker drag forces. The effect of the slot density appears to be stronger for larger slot width.

Figure 6(l) and **7(l)** show higher produced fines for lower slot densities. The reason is the lower OFA for the lower density, resulting in higher flow velocities at the constant flow rate, hence, stronger drag forces.

Results shown in **Fig. 6(e)-6(j)** and **7(e)-7(j)** indicate small produced fines sizes and low fines concentration for typical SAGD production rates (≈1.0 bbl/day/ft). The figures also indicate the high sensitivity of the fines size and concentrations to the flow rate. This may explain field observations which indicate plugging due to the aggressive flow rates (Williamson et al., 2016). As some slots are plugged, the flow from open slots increases, resulting in higher fines concentration and coarser produced fines. The increase in the size of the mobilized fines facilitates the formation of a bridge at the pore channels, hence, increases the plugging potential (De Zwart 2007).

CONCLUSION

This paper presents the results of pre-packed SRT testing to study the role of slot width and slot density on fines production and accumulation above the screen. Different multi-slot coupons with slot densities of 30, 42 and 54 SPC and slot widths ranging from 0.010" to 0.032" were used in the test matrix. Slot widths cover the lower and upper bound slot widths obtained by using the existing design criteria for two representative PSDs in the McMurray Formation in Alberta.

The brine used in the testing was synthetized by dissolving NaCl, which is a monovalent salt, in distilled water. The use of NaCl seems to result in a brine with the most adverse effect due to its ability to interact with Kaolinite and Illite and mobilize them. All tests were performed at a constant pH and salinity level (pH=7.9; Salinity= 0.7%).

Brine was injected at different rates more than 10 times the typical flow rates in SAGD operations (40 ml/hr/slot) into a sand pack with similar PSD and grain shapes to a typical oil sand from the McMurray Formation (medium size sand DC-III, and fine sand DC-II).

High flow rates were tested to simulate extreme cases where local plugging of slots results in increased fluid velocities in the open slots. The total pore volume injected during each test was constant for each PSD.

The pressure drop across the slotted liner coupon was found to be negligible (less than 0.01 psi) for the range of flow rates that was tested for the single-phase brine injection as no slot plugging was observed during the tests. Therefore, the study focused on the fines/clay migration, which affects the permeability of the filtrate in the vicinity of the slotted liner coupon by reducing the filtrate permeability.

Results indicate drastic increase of fines concentration above the screen for small slot widths, that can lead to pore plugging, hence, low wellbore productivity. In the contrary, the increase of fines concentration above the coupon after injecting brine with the total volume of over 20 times the pore volume is still negligible for wider slots.

It is evident that the fluid flow rate plays a critical role in mobilizing and transporting the fines. However, the role of slot width and density seems to also be crucial. The concentration and size of produced fines is highly affected by the slot size and density. The slot width highly affects the concentration and size of the produced fines. As the slot width increases, the size and concentration of the produced fines increases and the concentration of the fines above the slotted liner reduces. As the slot density increases, the concentration and size of the produced fines decreases. Increase in the slot density also reduces the concentration of the fines above the screen. This implies that for a given sand, increasing the slot width and slot density reduces the plugging tendency of the screen due to the fines migration.

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NOMENCLATURE

DAQ	Data Acquisition
D_{10}	Upper 10% on a PSD curve of the percentage passed through the sieve
D_{50}	Median size on the PSD curve
OFA	Open to Flow Area
PSD	Particle Size Distribution
PV	Pore Volume
SAGD	Steam Assisted Gravity Drainage
SPC	Slot per Column (number of slot in one column of 7" liner)
SRT	Sand Retention Test
w	Slot width (1/1000 inch)

REFERENCES

Abram, M., and Cain, G. 2014. Particle-Size Analysis for the Pike 1 Project, McMurray Formation. *J. Can. Pet. Technol.* **53**(6): 339-354. SPE-173890-PA.

Abrams, A. 1977. Mud Design to Minimize Rock Impairment Due to Particle Invasion. *J. Pet. Techno.l*, **29**(5): 587-892.

Barkman, H., and Davidson, H. 1972. Measuring Water Quality and Predicting Well Impairment. *J. Pet. Technol.*, **24**(7): 865-873.

Bennion, B., Gittins, S. and Gupta, S. et al. 2008. Protocols for Slotted Liner Design for Optimum SAGD Operation. Presented at the Canadian International Petroleum Conference/SPE Gas Technology Symposium Joint Conference, Calgary, Alberta, 17 -19 June. SPE-130441-MS.

Blunt, J. M., Bijeljic, B., Dong, et al. 2013. Pore-scale imaging and modelling. *Adv. Water Resour.*, **51**(2013):197-216.

Coberly, C.J. 1937. Selection of Screen Openings for Unconsolidated Sands, *Drilling and Production Practice*, January 1, New York, API-37–189.

De Zwart, A. 2007. Investigation of Clogging Processes in Unconsolidated Aquifers near Water Supply Wells. Delft University of Technology, Delft, The Netherland.

Fermaniuk, B. 2013. *Sand Control in Steam Assisted Gravity Drainage (SAGD) Wellbores and Process of Slotted Liner Design and Process*. Master of Engineering thesis, University of Calgary.

Fermaniuk, B., Claerhout, M., and Zhu, D. 2015. In-Situ SAGD Thermal-Chemical Effects and Metal-Bond Coated Slotted Liner Design for Enhanced Sand Control, Flow and Long Term Performance. Presented at SPE Thermal Well Integrity and Design Symposium, Banff, AB, 23-25 November. SPE-178465-MS.

Goodman, W.H, Godfrey, M.R., and Miller, T.M. 2010. Scale and Deposit Formation in Steam Assisted Gravity Drainage (SAGD) Facilities. Presented at the International Water Conference in San Antonio, Texas, 24-28 October.

Harris, C., and Odom, C. 1982. Effective Filtration in Completion and other Wellbore Operations Can be Good Investment. *Oil Gas J.* **80**:38-46.

Kaiser, T., Wilson, S., and Venning, L. 2000. Inflow Analysis and Optmization of Slotted Liners. Presented at the International Conference on Horizontal Well Technology, Calgary, Alberta, 6-8 November. SPE-65517-MS.

Kovacs, G. 1981. *Seepage Hydraulics*, Elsevier Scientific.

Ladd, S. 1978. Preparing Test Specimen Using Under Compaction, *Geotech. Testing J.*, **1**(1):16-23.

Mahmoudi, M., Fattahpour, V., Nouri, A. et al. 2015. Oil Sand Characterization for Standalone Screen Design and Large-Scale Laboratory Testing for Thermal Operations. Presented at the SPE Thermal Well Integrity and Design Symposium held in Banff, Alberta, Canada, 23–25 November, SPE-178470-MS.

Mahmoudi, M., Roostaei, M., and Ghalambor, A. 2016a. Sand Screen Design and Optimization for Horizontal Wells Using Reservoir Grain Size Distribution Mapping. Presented at the SPE International Conference and Exhibition on Formation Damage Control, 24-26 February, Lafayette, Louisiana, SPE-179036-MS.

Mahmoudi, M., Fattahpour, V., Nouri, A. et al. 2016b. An Experimental Investigation of the Effect of pH and Salinity on Sand Control Performance for Heavy Oil Thermal Production. Presented at the SPE Canada Heavy Oil Technical Conference, 7-9 June, Calgary, Alberta, Canada, SPE-180756-MS.

Mukunoki, T., Miyata, Y., Mikami, K. et al. 2016. X-ray CT analysis of pore structure in sand. *Solid Earth Discuss*, **7**(2016):929–942.

Nabawy, B., Géraud, Y. Rochette, P. et al. 2009. Pore-throat Characterization in Highly Porous and Permeable Sandstones, *AAPG Bull.*, **93**(6):719–739.

Pittman, E.D. 1992. Relationship of Porosity and Permeability to Various Parameters Derived from Mercury Injection-Capillary Pressure Curves for Sandstone. *AAPG Bull.*, **76**(5):191-198.

Pittman, E.D. 2001. Estimating Pore Throat Size in Sandstones from Routine Core-Analysis Data. Search and Discovery Article #40009.

Prins, J. 2003. *Suspended Material in Abstracted Groundwater in the Netherlands*. M.Sc. Thesis, Utrecht University, Utrecht.

Romanova, U., and Ma, T. 2013. An Investigation on the Plugging Mechanisms in a Slotted Liner from the Steam Assisted Gravity Operations. Presented at the SPE European Formation Damage Conference, Noordwijk, The Netherland, 5-7 June. SPE-165111-MS.

Schulien, S., Ovsthus, J., Hestenes, A. et al. 1997. Scale Formation and Treatment in and around Sand Control Screens. Presented at the SPE International Symposium on Oilfield Chemistry, Houston, TX, 18-21 February. SPE-37305-MS.

Suman, G., Ellis, R., and Snyder, R. 1985. Sand Control Handbook. *Houston: Gulf publishing company.*

Uno, T., Kamiya, K., and Tanaka, K. 1998. The Distribution of Sand Void Diameter by Air Intrusion Method and Moisture Characteristic Curve Method. *Journal of Japan Society of Civil Engineering*, **603**(III-44):35-44.

Valdes, J. 2002. *Fines Migration and Formation Damage-Microscale Studies*. Ph.D. dissertation, Georgia Institute of Technology, Atlanta, Ga.

Van Oort, E., van Velzen, G., and Leerlooijer, K. 1993. Impairment by Suspended Solids Invasion: Testing and Prediction. *SPE Prod & Fac*, **8**(3): 178-184.

Williamson, H., Babaganov, A., Romanova, U. 2016. Unlocking Potential of the Lower Grand Rapids Formation, Western Canada: The Role of Sand Control and Operational Practices in SAGD Performance. Presented at the SPE Canada Heavy Oil Technical Conference, 7-9 June, Calgary, Alberta, Canada, SPE-180700-MS.

TABLES

Table 1. Average pore throat size calculated based on different methods

PSD	Porosity (%)	Permeability (md)	Average Pore size (µm)				Average pore size (µm)	$^1/_3$ rule	$^1/_7$ rule	$^1/_{14}$ rule	Critical Plugging range
			Harris and Odom (1982)	Uno et al. (1998)	Pittman (1992)	Nabawy et al. (2009)					
DC-II	30.8	3600	60.0	39.3	41.7	49.8	47.7	16.8	7.2	3.6	≈3.6-16.8
DC-III	39.6	4650	68.2	46.1	46.9	56.3	54.4	19.0	8.2	4.1	≈4.1-19

FIGURES

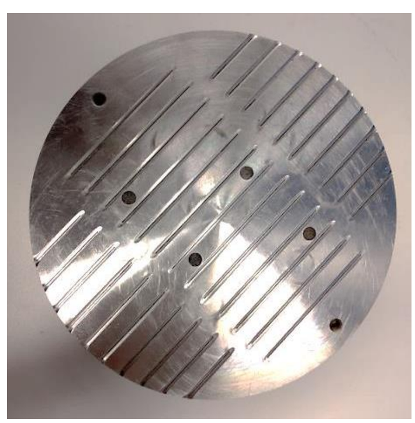


Figure 1. Multi-slot coupon with seamed slots of 0.022" to 0.014" width and 216 slots per foot density (After Mahmoudi et al. 2016b)

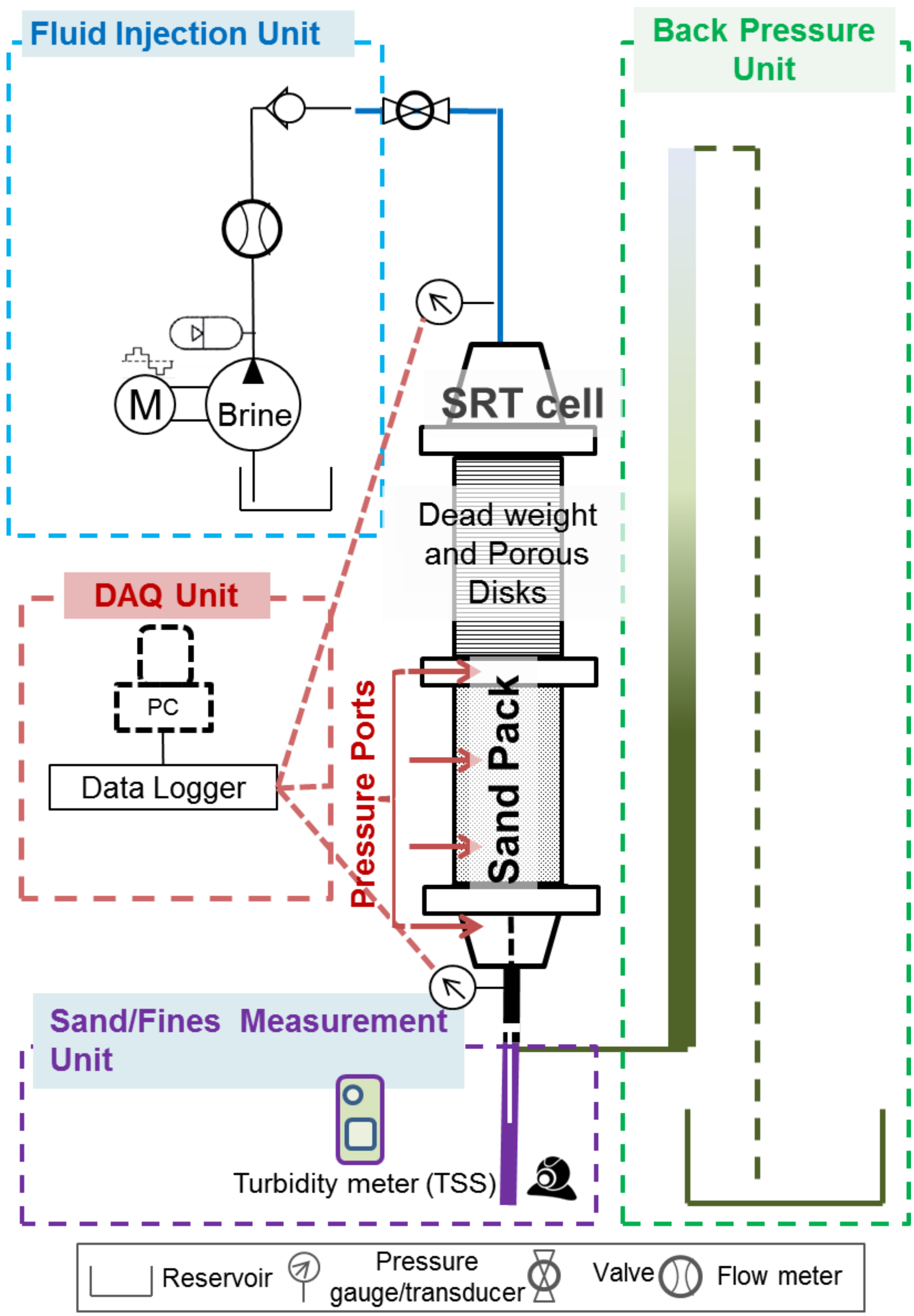


Figure 2. Schematic view of the different units of the SRT facility (After Mahmoudi et al. 2016b)

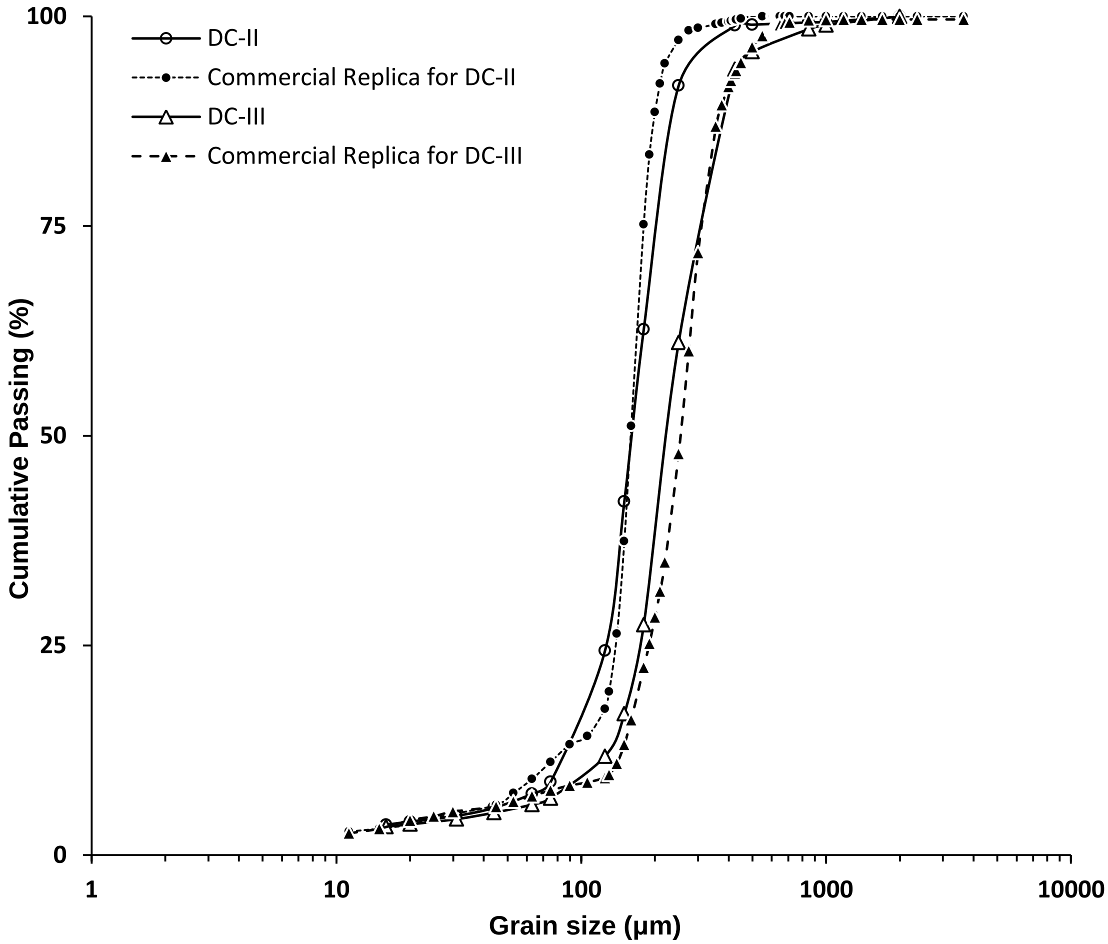


Figure 3. Particle size distribution of the tested sand packs and oil sands classes (DC-II and DC-III) categorized by Abram and Cain (2014)

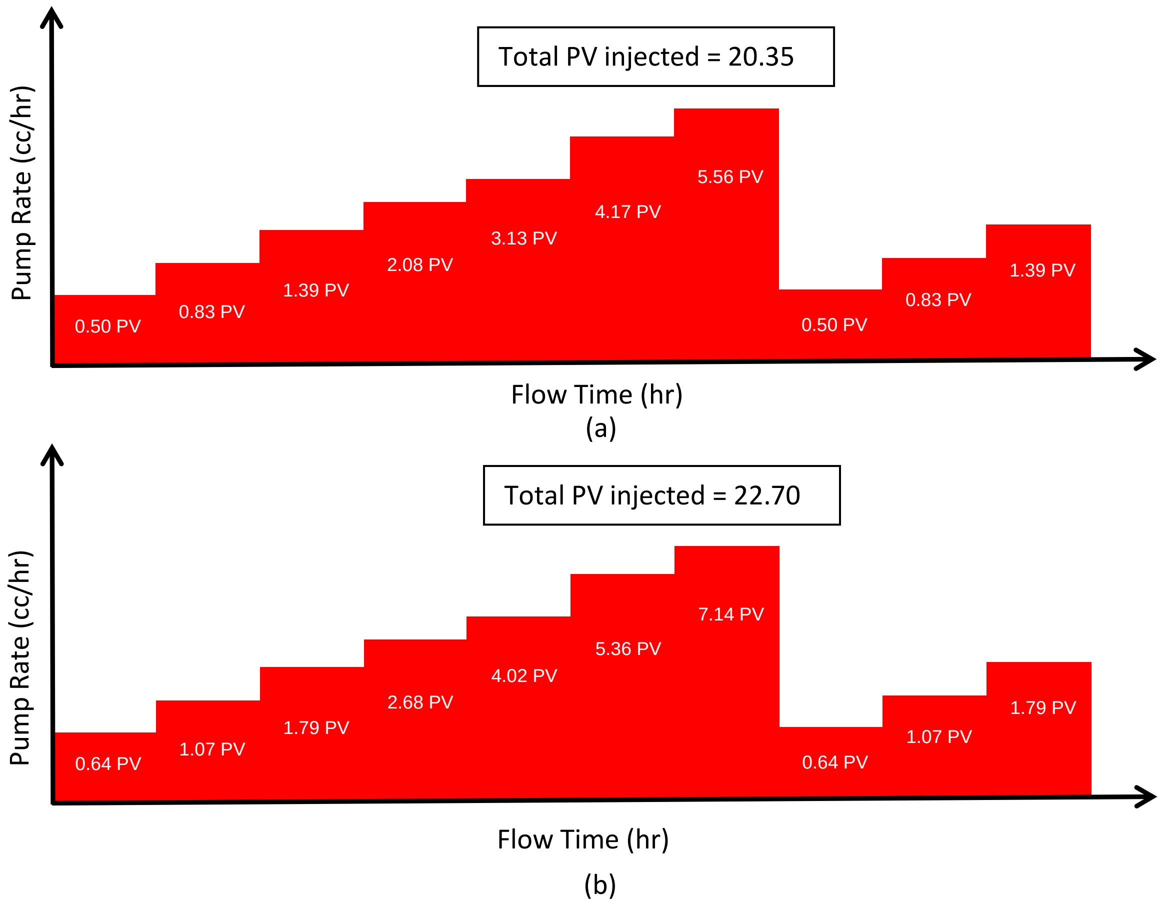


Figure 4. Injected PVs for step rate tests in pre-packed SRT tests on sand packs prepared by different PSDs: (a) DC-III and (b) DC-II

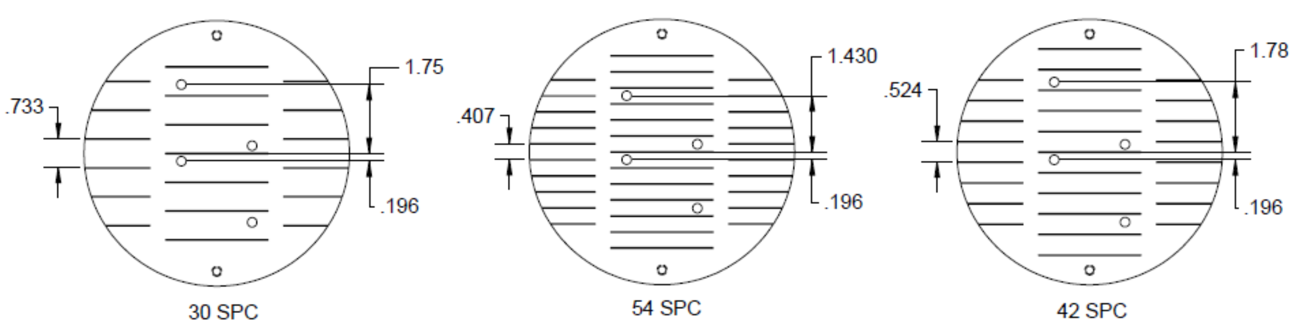
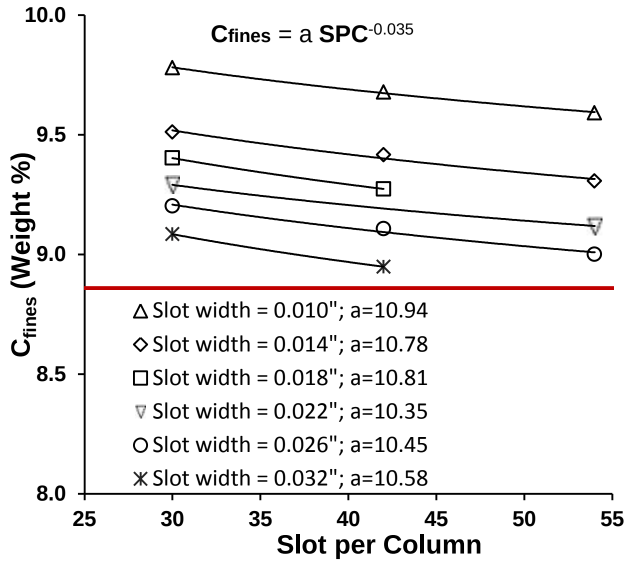
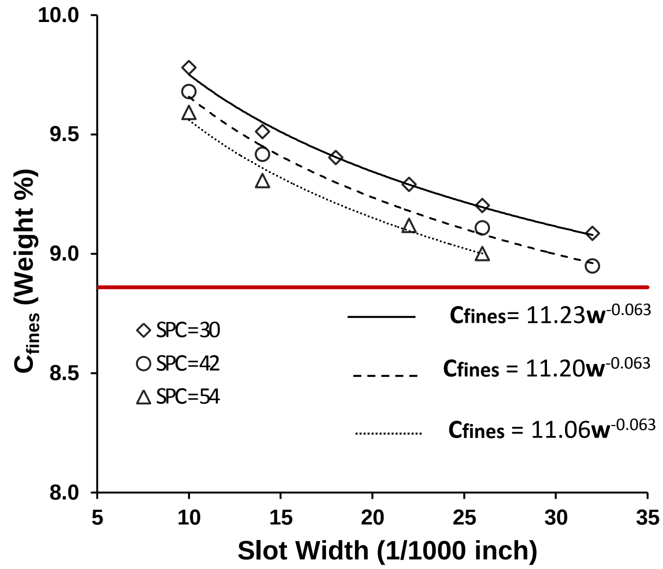


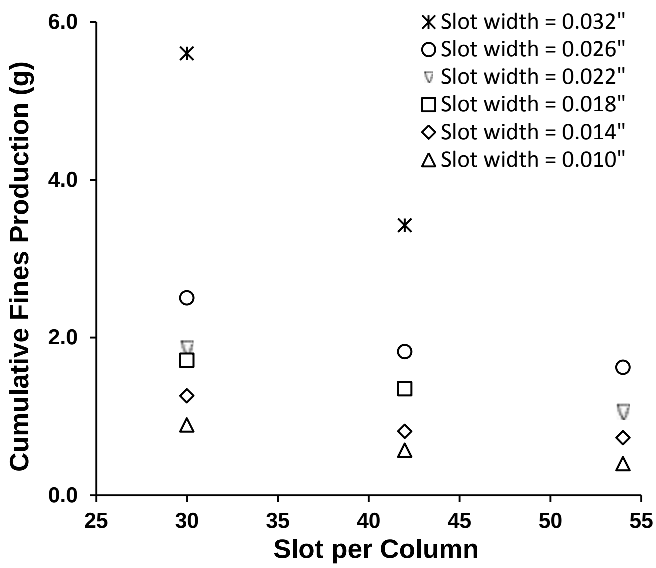
Figure 5. SPC and slot patterns of the tested coupons for pre-packed SRT tests; three SPC of 30, 42 and 54 and 6 slot widths of 0.018" to 0.010", 0.022" to 0.014", 0.026" to 0.018", 0.030" to 0.022", 0.032" to 0.026", and 0.040" to 0.032"are tested. All dimensions are in inches.


Cfines = a SPC-0.035
Cfines (Weight %)
Slot width = 0.010"; a=10.94
Slot width = 0.014"; a=10.78
Slot width = 0.018"; a=10.81
Slot width = 0.022"; a=10.35
Slot width = 0.026"; a=10.45
Slot width = 0.032"; a=10.58
Slot per Column

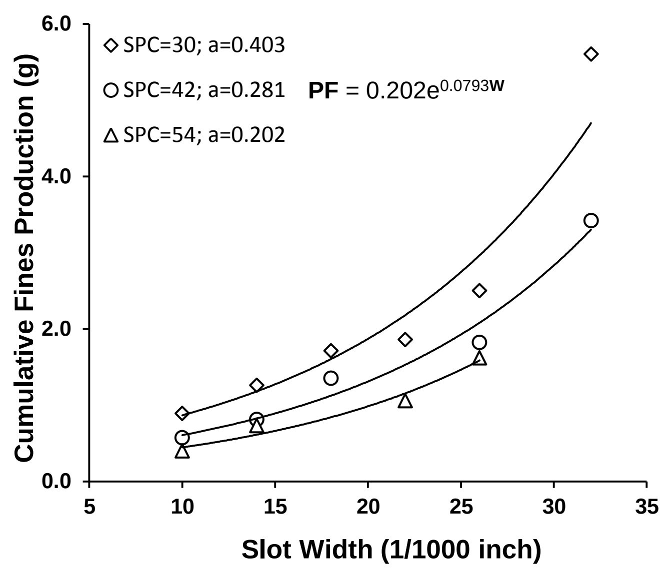
(a)


Cfines (Weight %)
SPC=30
SPC=42
SPC=54
Cfines= 11.23w-0.063
Cfines = 11.20w-0.063
Cfines = 11.06w-0.063
Slot Width (1/1000 inch)

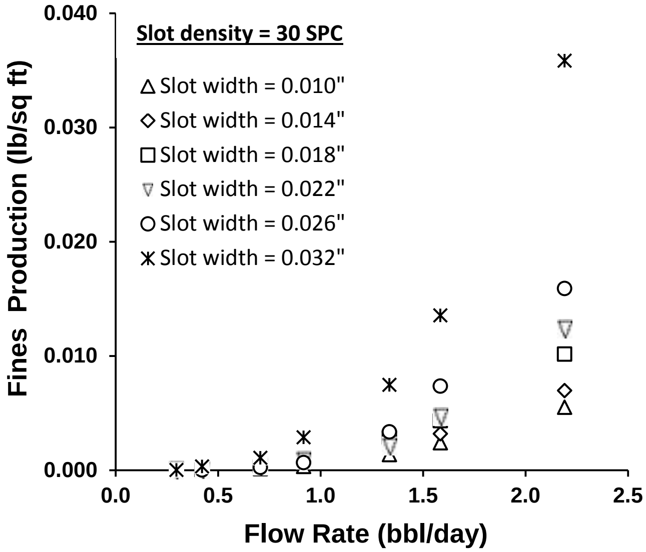
(b)


Cumulative Fines Production (g)
Slot width = 0.032"
Slot width = 0.026"
Slot width = 0.022"
Slot width = 0.018"
Slot width = 0.014"
Slot width = 0.010"
Slot per Column

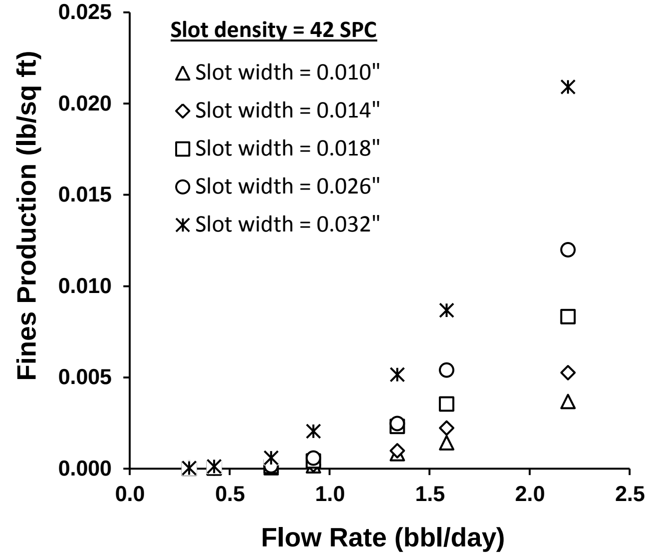
(c)


Cumulative Fines Production (g)
SPC=30; a=0.403
SPC=42; a=0.281
PF = 0.202e0.0793W
SPC=54; a=0.202
Slot Width (1/1000 inch)

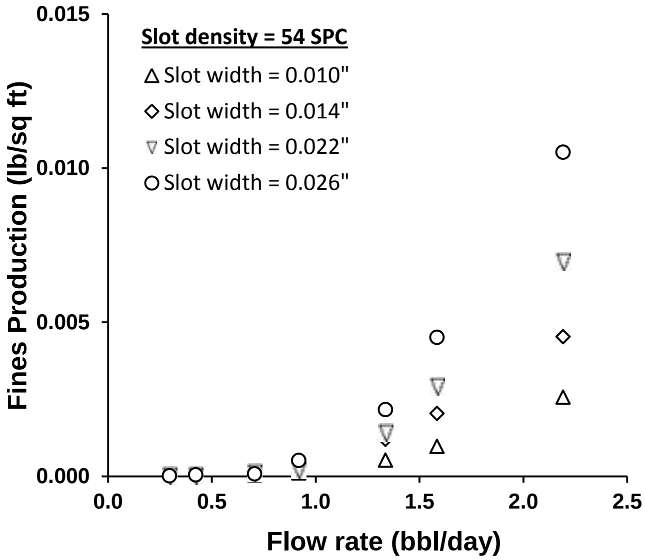
(d)


Slot density = 30 SPC
Slot width = 0.010"
Slot width = 0.014"
Slot width = 0.018"
Slot width = 0.022"
Slot width = 0.026"
Slot width = 0.032"
Fines Production (lb/sq ft)
Flow Rate (bbl/day)
0.000
0.010
0.020
0.030
0.040
0.0
0.5
1.0
1.5
2.0
2.5

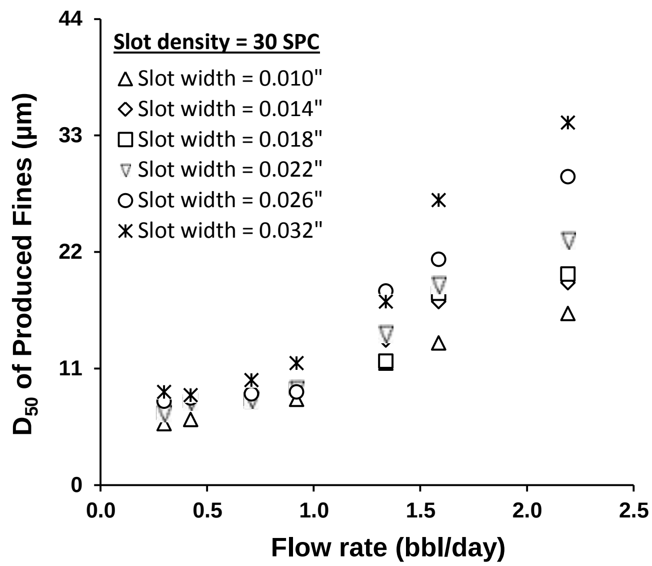
(e)


Slot density = 42 SPC
Slot width = 0.010"
Slot width = 0.014"
Slot width = 0.018"
Slot width = 0.026"
Slot width = 0.032"
Fines Production (lb/sq ft)
Flow Rate (bbl/day)
0.000
0.005
0.010
0.015
0.020
0.025
0.0
0.5
1.0
1.5
2.0
2.5

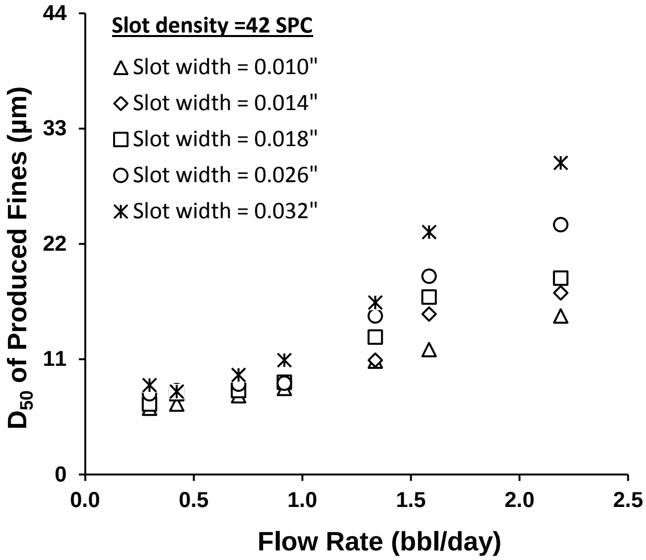
(f)


Slot density = 54 SPC
Slot width = 0.010"
Slot width = 0.014"
Slot width = 0.022"
Slot width = 0.026"
Fines Production (lb/sq ft)
Flow rate (bbl/day)
0.000
0.005
0.010
0.015
0.0
0.5
1.0
1.5
2.0
2.5

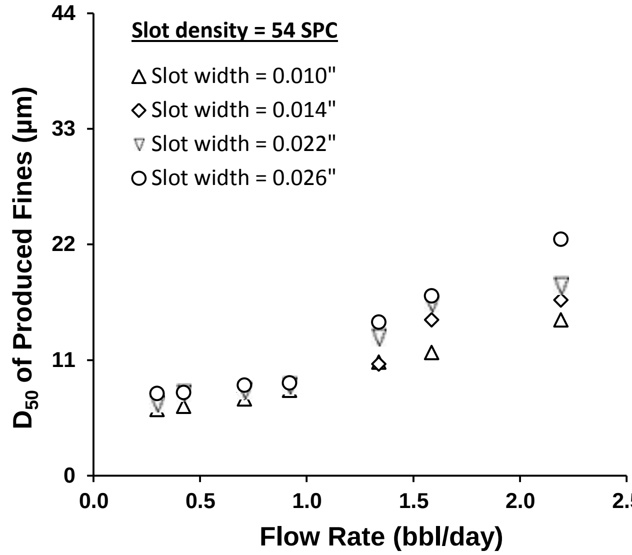
(g)


Slot density = 30 SPC
Slot width = 0.010"
Slot width = 0.014"
Slot width = 0.018"
Slot width = 0.022"
Slot width = 0.026"
Slot width = 0.032"
D50 of Produced Fines (μm)
Flow rate (bbl/day)
0
11
22
33
44
0.0
0.5
1.0
1.5
2.0
2.5

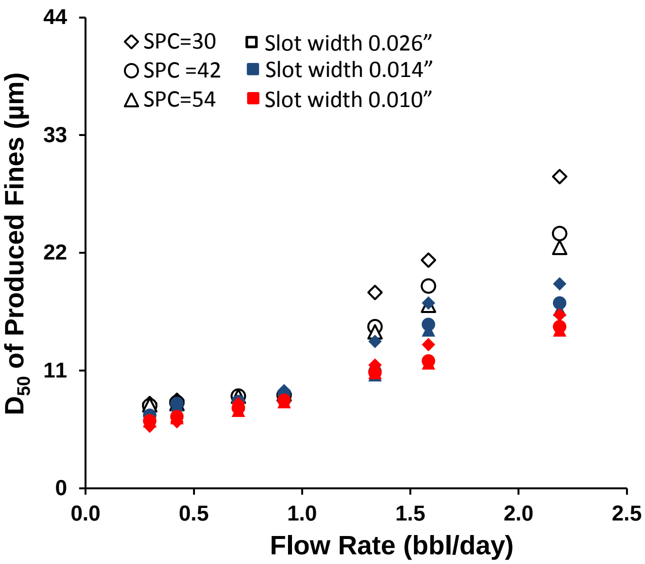
(h)



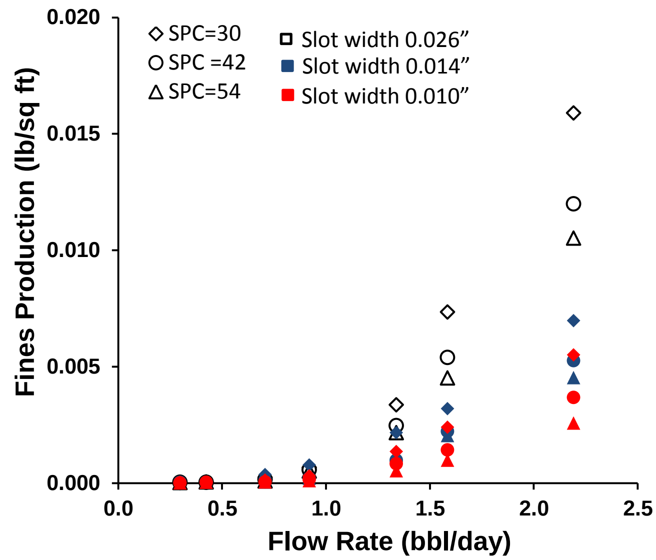
(i)



(j)

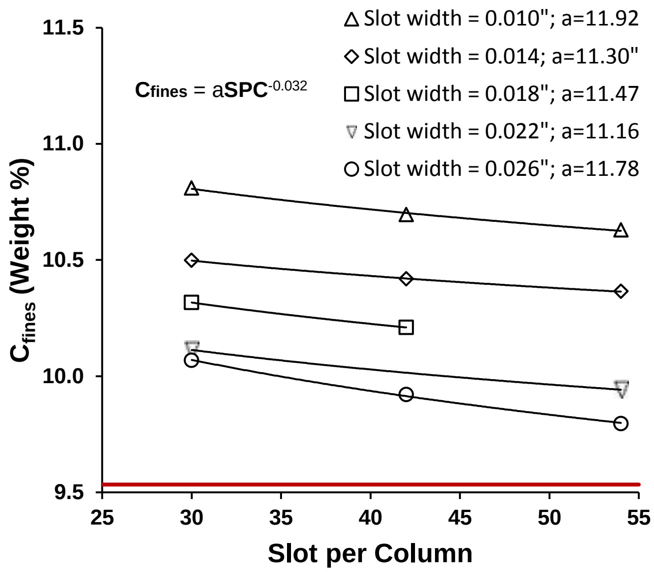


(k)



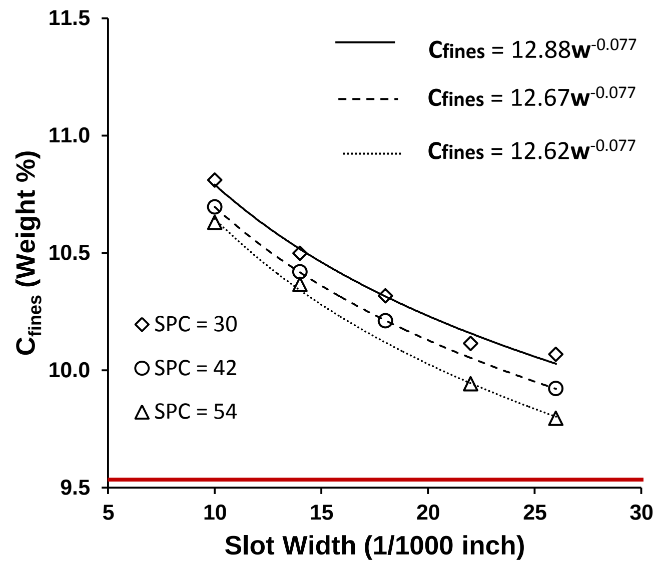
(l)

Figure 1. Results of the slot density and width effect for DC-III: (a) effect of slot density on the concentration of fines in vicinity of the screen, (b) effect of slot width on the concentration of fines in vicinity of the screen, (c) effect of slot density on the cumulative fines production (d) effect of slot size on the cumulative fines production, (e) effect of slot size on the fines production, for each flow rate step, at slot density of SPC=30, (f) effect of slot size on the fines production, for each flow rate step, at slot density of SPC=42, (g) effect of slot size on the fines production, for each flow rate step, at slot density of SPC=54 (h) D_{50} of the produced fines for different flow rates at constant slot density (SPC=30) for different slot width, (i) D_{50} of the produced fines for different flow rates at constant slot density (SPC=42) for different slot width, (j) D_{50} of the produced fines for different flow rates at constant slot density (SPC=54) for different slot width, (k) D_{50} of the produced fines for different flow rates for different slot density and width and (l) fines production in each flow rate step for different slot density and width.



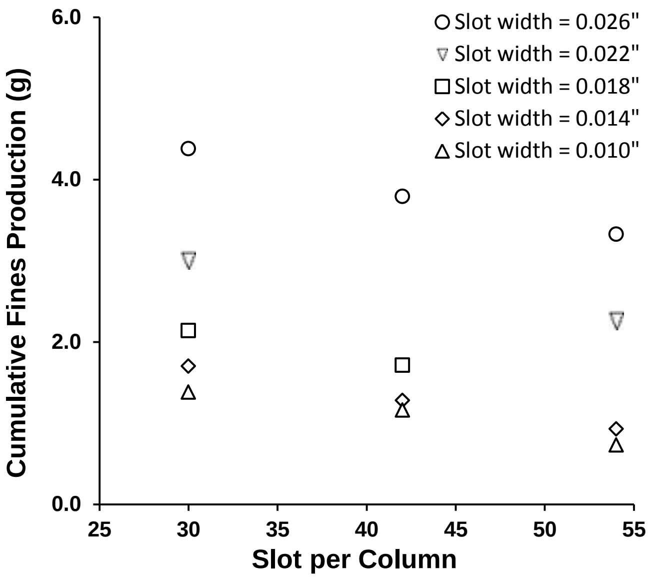
Slot width = 0.010"; a=11.92
Slot width = 0.014; a=11.30"
Slot width = 0.018"; a=11.47
Slot width = 0.022"; a=11.16
Slot width = 0.026"; a=11.78
Cfines = aSPC-0.032
Cfines (Weight %)
Slot per Column
11.5
11.0
10.5
10.0
9.5
25
30
35
40
45
50
55

(a)



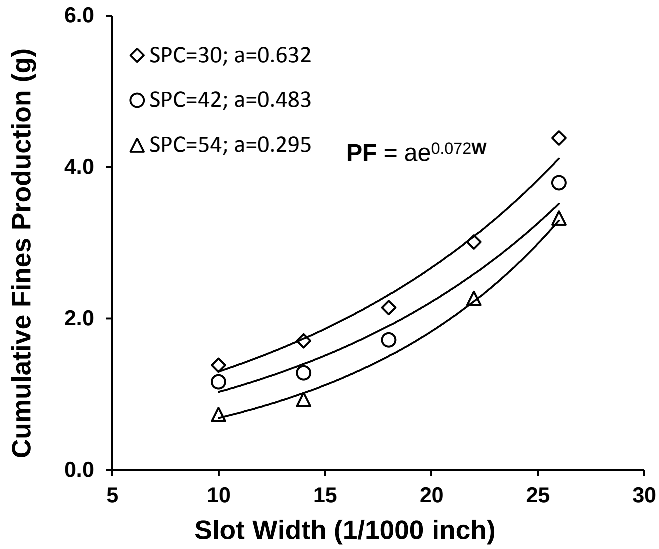
Cfines = 12.88w-0.077
Cfines = 12.67w-0.077
Cfines = 12.62w-0.077
SPC = 30
SPC = 42
SPC = 54
Cfines (Weight %)
Slot Width (1/1000 inch)
11.5
11.0
10.5
10.0
9.5
5
10
15
20
25
30

(b)



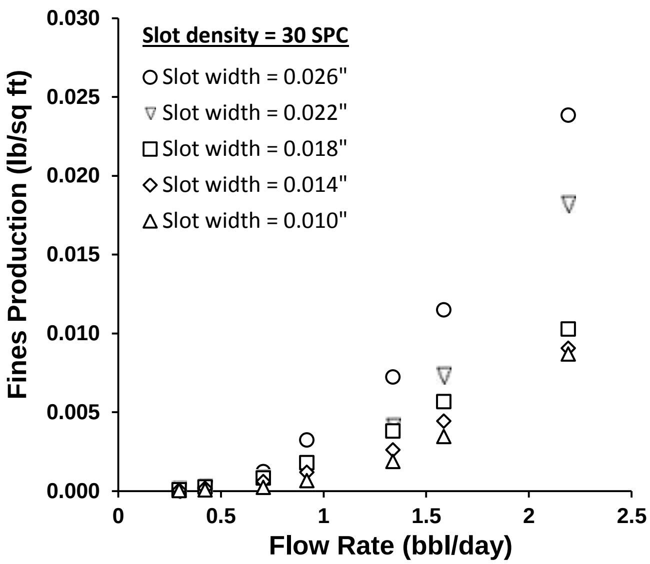
Slot width = 0.026"
Slot width = 0.022"
Slot width = 0.018"
Slot width = 0.014"
Slot width = 0.010"
Cumulative Fines Production (g)
Slot per Column
6.0
4.0
2.0
0.0
25
30
35
40
45
50
55

(c)

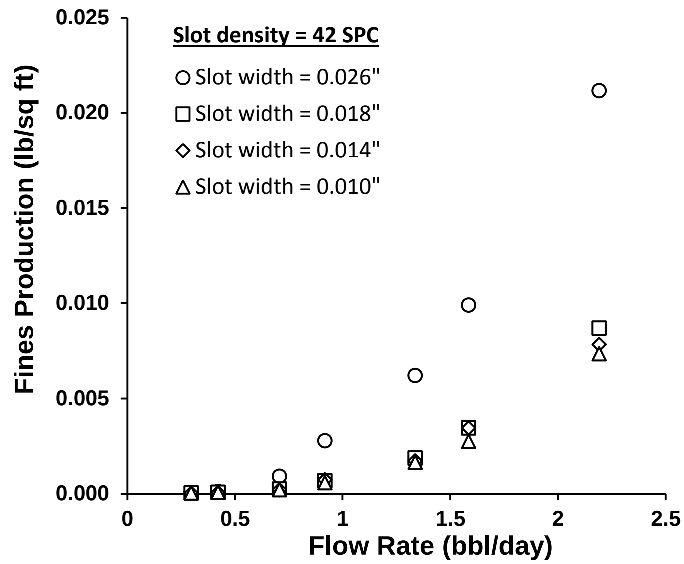


SPC=30; a=0.632
SPC=42; a=0.483
SPC=54; a=0.295
PF = ae0.072w
Cumulative Fines Production (g)
Slot Width (1/1000 inch)
6.0
4.0
2.0
0.0
5
10
15
20
25
30

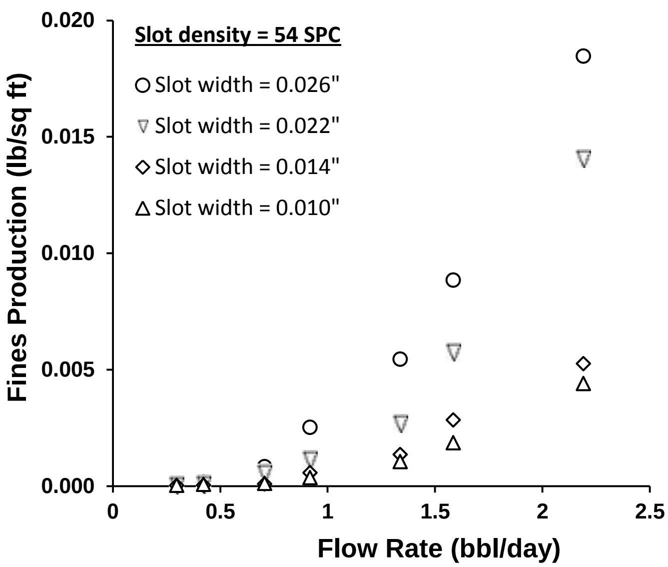
(d)


Slot density = 30 SPC
Slot width = 0.026"
Slot width = 0.022"
Slot width = 0.018"
Slot width = 0.014"
Slot width = 0.010"
Fines Production (lb/sq ft)
Flow Rate (bbl/day)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
0.5
1
1.5
2
2.5

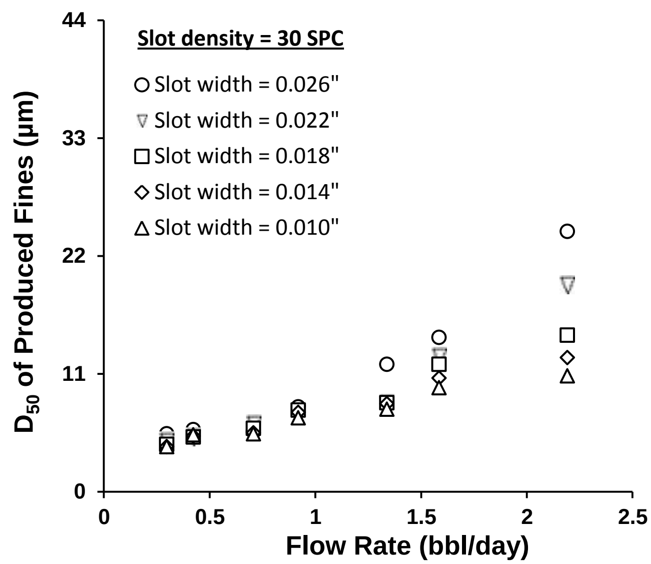
(e)


Slot density = 42 SPC
Slot width = 0.026"
Slot width = 0.018"
Slot width = 0.014"
Slot width = 0.010"
Fines Production (lb/sq ft)
Flow Rate (bbl/day)
0.025
0.020
0.015
0.010
0.005
0.000
0
0.5
1
1.5
2
2.5

(f)


Slot density = 54 SPC
Slot width = 0.026"
Slot width = 0.022"
Slot width = 0.014"
Slot width = 0.010"
Fines Production (lb/sq ft)
Flow Rate (bbl/day)
0.020
0.015
0.010
0.005
0.000
0
0.5
1
1.5
2
2.5

(g)


Slot density = 30 SPC
Slot width = 0.026"
Slot width = 0.022"
Slot width = 0.018"
Slot width = 0.014"
Slot width = 0.010"
D_{50} of Produced Fines (μm)
Flow Rate (bbl/day)
44
33
22
11
0
0
0.5
1
1.5
2
2.5

(h)

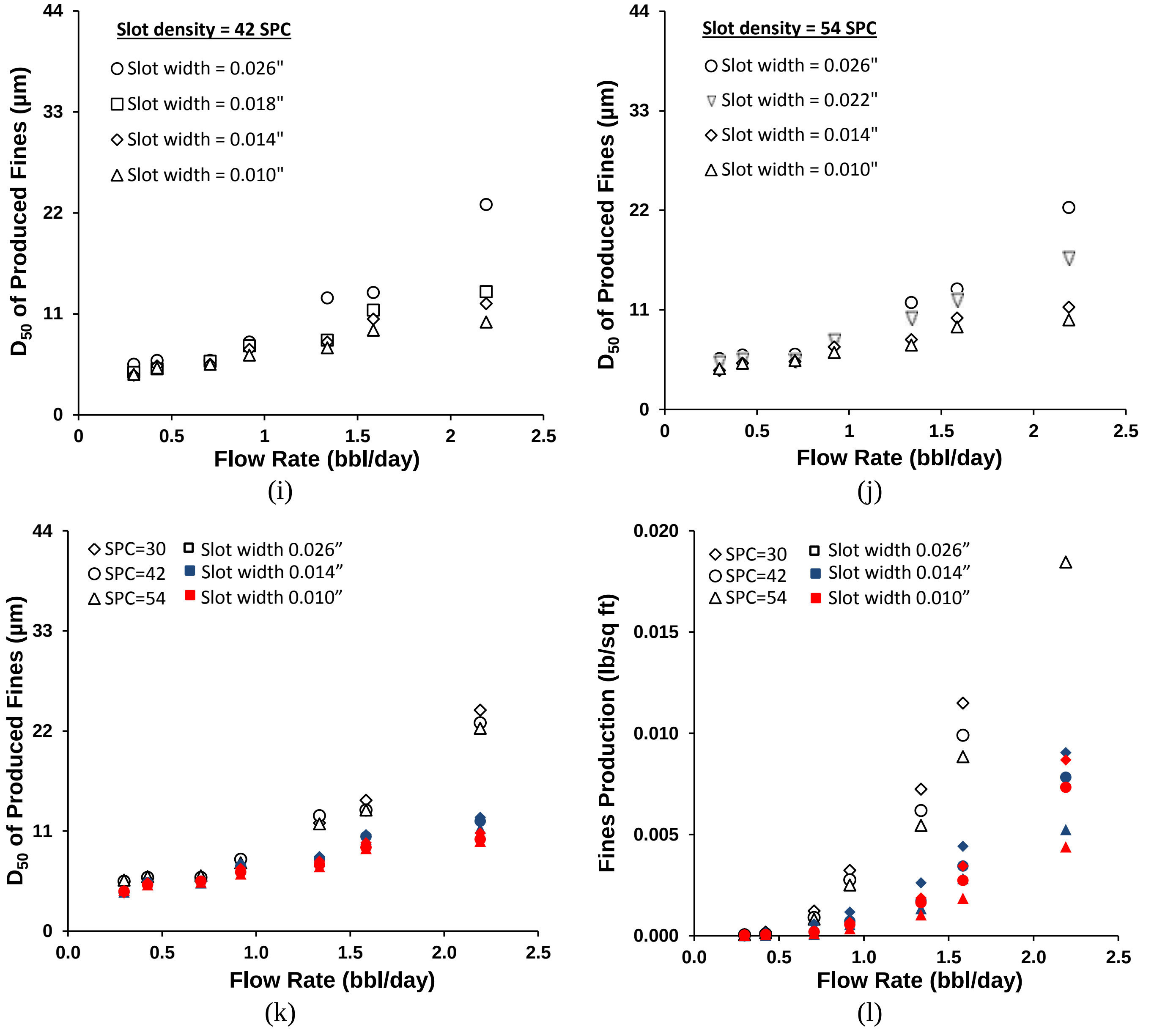


Figure 2. Results of the slot density and width effect for DC-II: (a) effect of slot density on the concentration of fines in vicinity of the screen, (b) effect of slot width on the concentration of fines in vicinity of the screen, (c) effect of slot density on the cumulative fines production (d) effect of slot size on the cumulative fines production, (e) effect of slot size on the fines production, for each flow rate step, at slot density of SPC=30, (f) effect of slot size on the fines production, for each flow rate step, at slot density of SPC=42, (g) effect of slot size on the fines production, for each flow rate step, at slot density of SPC=54 (h) D_{50} of the produced fines for different flow rates at constant slot density (SPC=30) for different slot width, (i) D_{50} of the produced fines for different flow rates at constant slot density (SPC=42) for different slot width, (j) D_{50} of the produced fines for different flow rates at constant slot density (SPC=54) for different slot width, (k) D_{50} of the produced fines for different flow rates for different slot density and width and (l) fines production in each flow rate step for different slot density and width.