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Aperture Design Optimization of Wire-Wrapped Screens for SAGD Production Wells

Jesus David Montero Pallares [1,2], Chenxi Wang [1,3], Mohammad Haftani [1] and Alireza Nouri [1,*]

[1] Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB T6G 2E3, Canada
[2] Gran Tierra Energy, Calgary, AB T2P 0R3, Canada
[3] China National Offshore Oil Corporation (CNOOC) Research Institute Ltd., China National Offshore Oil Corporation, Beijing 100028, China
* Correspondence: anouri@ualberta.ca

Abstract: Wire-wrapped screens have been established as one of the primary sand control devices in Steam-Assisted Gravity Drainage (SAGD) wells due to the high open-to-flow area and superior plugging attributes. However, their design is still a point of interest for thermal operations. Generally, existing approaches rely on one or more particular points of reservoir sands' particle size distribution (PSD) and rules of thumb inferred from other devices like the slotted liners. This study used Sand Retention Testing (SRT) to analyze the performance of WWS under various testing conditions, which were neglected in the current design criteria. The experimental investigation leads to a set of graphical design criteria that provide an optimum aperture size window. The results show that the sand retention performance of WWS is highly dependent on the flow velocities of the wetting phase. Moreover, the testing showed satisfactory plugging performance of WWS even with narrow aperture sizes, proving a superior performance for low-quality oil sands.

Keywords: wire wrapped screen; design criteria; traffic light system; SAGD; sand control

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1. Introduction

SAGD is the primary technology to extract heavy oil from oil sands. The continuous steam injection from the upper well generates a growing steam chamber that contacts and transfers heat to the bitumen. Consequently, oil viscosity is reduced, which allows the gravity-assisted flow of melted bitumen and condensed steam toward the lower production well [1] (Figure 1a,b).

Oil sands are geologically young formations typically found at shallow depths (up to 450 m) [2]. The inherent loose characteristic of oil sands requires sand control methods to avoid damage in surface and downhole facilities [3]. Sand particles are erosive at high flow velocities [4], and their accumulation in horizontal wells can obstruct the free flow of production fluids, leading to remedial workover operations and high treatment costs [5]. Over the years, SAGD operators have employed Standalone Screens (SAS) to provide sand control and mechanical support to the wellbore. Slotted Liner (SL), Wire-Wrapped Screen (WWS), and Punched Screens (PS) are the most common sand control devices (SCD) in SAGD wells (Figure 1c,e).

The screen would form sand bridges over the slots, providing retention of sand grains [6]. The relatively low flow rates in SAGD wells prompted the operators to opt for SL as a low-cost option with robust mechanical integrity [7,8]. However, SL may exhibit severe plugging tendencies and corrosion issues, resulting in a gradual shift from SL to higher OFA screens, such as WWS and PS [9,10]. WWS consists of a continuous profiled wire wrapped onto a base pipe (Figure 1d). The wires typically have a trapezoid cross-section and are supported by ribs or rods in direct contact with a perforated pipe. The hole density on the base pipe affects the integrity and strength of the screen, which is out of the scope of the current study. WWS provides a high OFA, from 6% to 15%, compared to 2–3% for SL and 3–8% for PS [11].

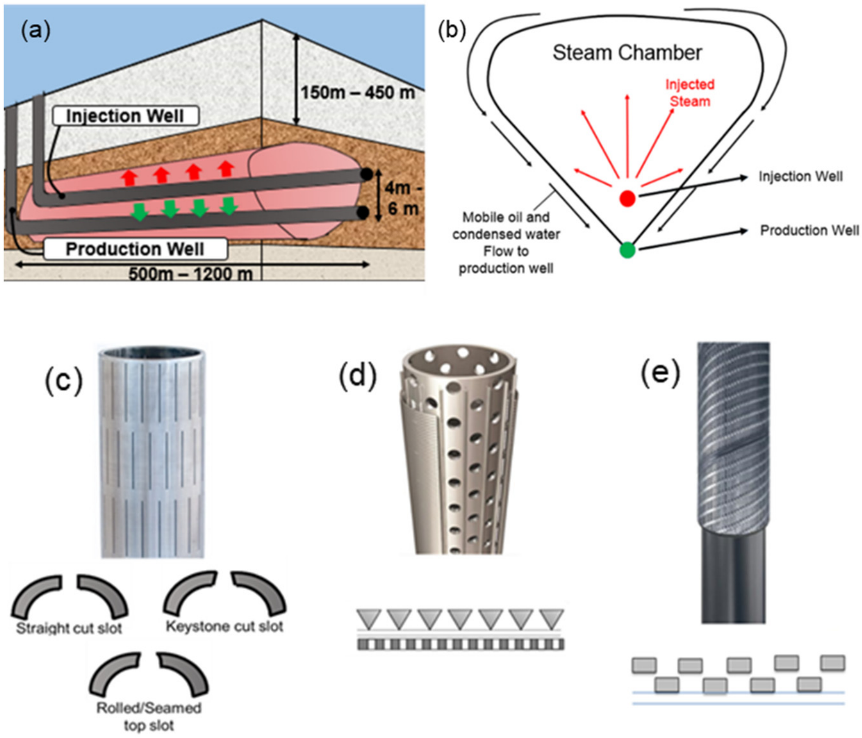


Figure 1. (**a**) A schematic of the SAGD process, (**b**) steam chamber, (**c**–**e**) the depiction of sand control devices and their respective slot geometry, (**c**) Slotted Liner, (**d**) Wire-Wrapped Screens, and (**e**) Punched Screens.

A sand control screen optimization effort minimizes sand production while keeping an acceptable flow performance throughout wellbore life [7]. Generally, the screen aperture is the crucial parameter in sanding [8,12], whereas OFA dominates the flow response of the device [13]. The lower the OFA, the faster a device can achieve severe plugging. WWS offers the benefit of high OFA and has proven more effective for low-quality sands with active clay components [14]. Increasing the slot density for SL generates a slight increase in OFA, while varying the aperture size in WWS can drastically escalate the OFA.

This study aims to elaborate a new set of criteria using the "Traffic Light System" (TLS) method to identify the optimum aperture window for the McMurray Formation PSD classes. The criteria employ the experimental data to discretize the performance into different production scenarios, accounting for sanding and flow performance. The operational procedure incorporates various flow velocities and fluid phases to gain an insight into the WWS performance.

2. Existing Aperture Design Criteria

Over time, several authors have tried to develop criteria for the sand control screen aperture selection. Coberly [15] introduced 2D10 as the maximum aperture at which stable bridges can form. D10 represents the sieve size that retains 10% of the material mass. Suman et al. [6] proposed a more conservative criterion (≤D10) but still recognized the importance of larger particles on bridge stability. Initial groundwater applications of WWS followed a sizing recommendation of D40 [16]. Subsequent criteria continued to rely on one single point of the PSD. For instance, Gillespie et al. [17] proposed 2D50 as the upper limit for WWS aperture size based on slurry SRT for different sand classes. Ballard and Beare [18] combined pre-packed and slurry SRT results to suggest aperture sizing on the D30 and stated that it provides better results than the D10 criteria. Likewise, Weatherford guidelines recommend D25 for WWS. Fattahpour et al. [8] presented a rule of thumb for SAGD wells after comparing experimental data with field applications, selecting WWS with apertures 0.004 to 0.008 inches less than the equivalent SL selection for the same sand. The existing aperture design criteria for WWS do not consider operational conditions, fluid properties, stress levels, or PSD shape.

3. Experimental Setup and Procedure

The investigation employs a pre-packed SRT that emulates the high-porosity zone formed around the sand control screen after borehole collapse. The experiment mimics the conditions around SAGD production wells using reasonable flow rates, fluid ratios, and production scenarios. All tests were conducted with 60 psi of axial stress to replicate the early stages of the near-wellbore region with relatively low effective stresses [19].

3.1. Experimental Apparatus

The pre-packed SRT equipment (Figure 2a) encompasses five units: (1) cell and accessories, (2) fluids injection unit, (3) data acquisition system, (4) collection and back-pressure units, and (5) load frame.

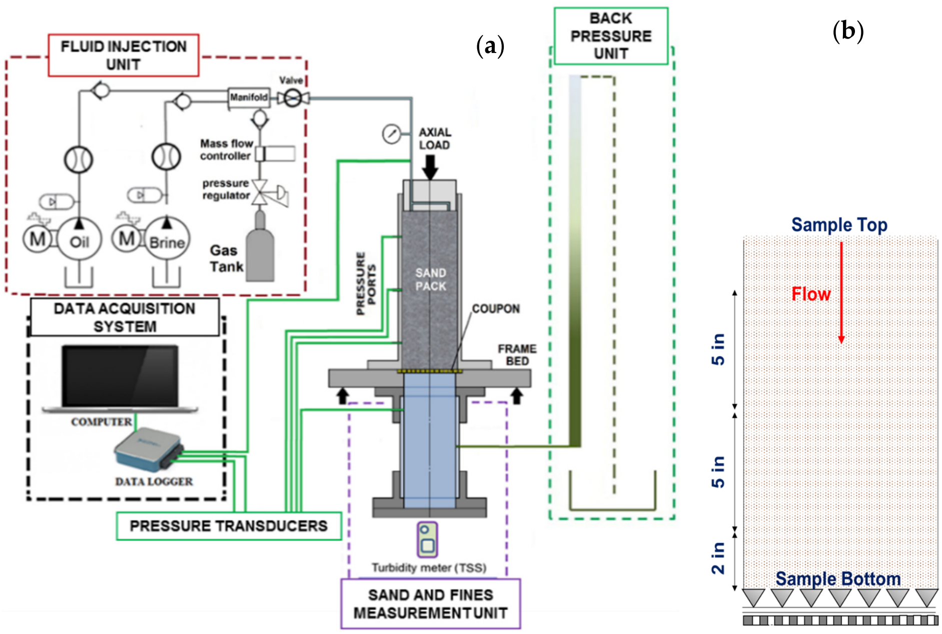


Figure 2. (**a**) Pre-packed SRT, schematic, (**b**) sand-pack sections. L_b, L_m, and L_t represent the length of near-screen, middle, and top intervals.

The core holder, 6 inches in diameter and 18.5 inches in length, accommodates the sand pack sitting over the sand control screen samples. Three connection points along the cell allow recording pressure drop evolution (Figure 2b) (differential transducers with 0.25% accuracy). The near-screen zone is defined as the 2-inch interval of sand above the screen. The other points are located 7 and 12 inches above the screen. Flow is injected from the top to the bottom of the sand pack and is then directed toward the back-pressure column, which provides 3 psi pressure at the sample bottom. Produced particles at each step are captured and accumulated in the sand trap.

3.2. Testing Materials

Several tests were performed on three representative PSD classes from the McMurray formation (DC-I to DC-III) to evaluate the response of WWS under different sand characteristics. DC-III is considered medium-coarse sand, while DC-II and DC-I are fine and very fine sands, respectively. The porosity of sand samples is about 35%. Synthetic sand mixtures using commercial sands, silts, and clays are employed to replicate the PSDs categorized by Abram and Cain [20]. Figure 3 compares commercial and actual formation sands. Table 1 describes each sample's detailed D-values and shape factors (uniformity coefficient and sorting coefficient). Mahmoudi et al. [21] showed that commercial mixtures also display similar strength properties and shape factors as the formation sands. Kaolinite was used as the clay mineral in the samples as it is the dominant clay in the McMurray Formation [21].

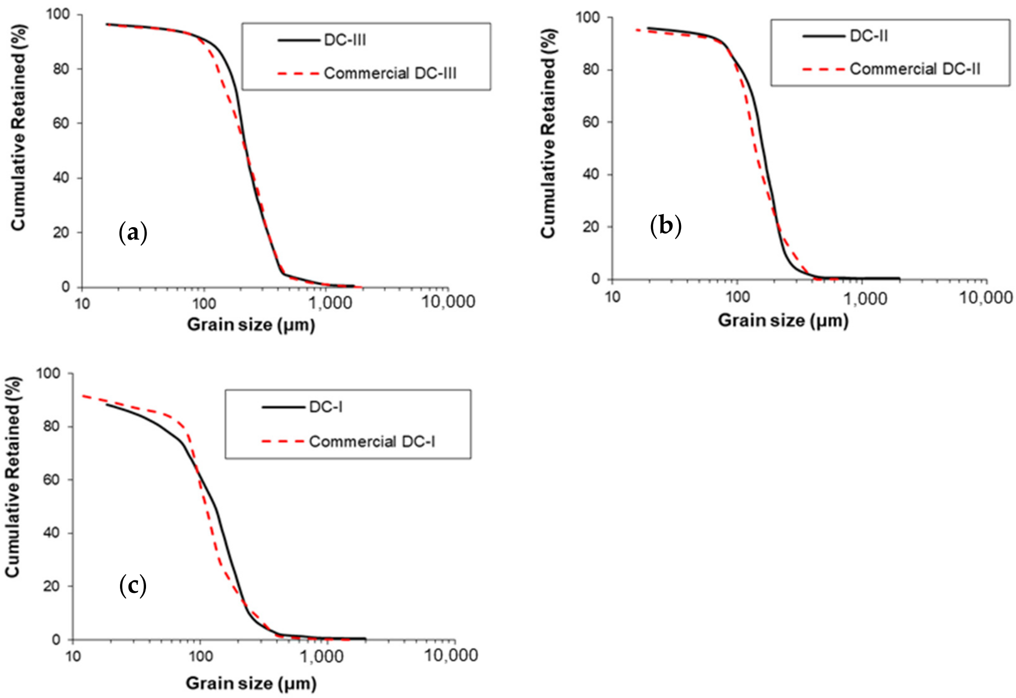


Figure 3. PSD of formation sands and corresponding synthetic samples; (**a**) DC-III, (**b**) DC-II, (**c**) DC-I.

Table 1. PSD Characteristics of the McMurray Formation Sands.

Sand	D90	D70	D50	D40	D10	Uniformity Coefficient	Sorting Coefficient
DC-I	25	80	135	147	232	5.9	9.3
DC-II	76	118	175	205	260	2.7	3.4
DC-III	110	187	215	264	341	2.4	3.1

Uniformity Coefficient (UC = D40/D90), Sorting Coefficient (SC = D10/D90)

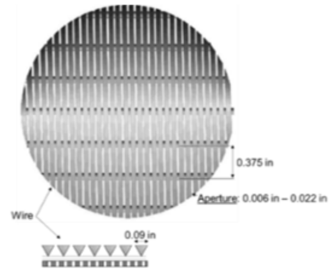
Figure 4a introduces the test matrix that covers existing criteria to incorporate both sanding and plugging conditions. Figure 4b shows a schematic with the design parameters of WWS coupons with 6 inches diameter. WWS coupons correspond to 6-inch-diameter disks cut from the screen. The performance of each sand is evaluated for different aperture sizes.

Haftani et al. [22] summarized the reported pH values of produced water from several SAGD projects, indicating the pH range from 7.3 to 8.8 with a wide range of salinity values. In this study, 7.9 is selected as the pH of the brine phase in all tests. Na^+ and Cl^- are the dominant ions encountered in produced water from SAGD wells, and 400 ppm was found to be the lowest value in SAGD wells [22], representing the worst-case scenario for fines migration.

Mineral oil with 8-cp viscosity is used to emulate bitumen at downhole temperature conditions [7]. Nitrogen is the gas phase used to represent steam-breakthrough episodes.

Aperture Size	PSD		
0.006"	DC-I	DC-II	DC-III
0.010"	DC-I	DC-II	DC-III
0.014"	DC-I	DC-II	DC-III
0.018"	DC-I	DC-II	DC-III
0.022"	-	-	DC-III

(a)



(b)

Figure 4. (**a**) Testing program and (**b**) schematic of WWS coupons with design specifications.

3.3. Testing Procedure

Sand preparation starts with the dry mixing of commercial sands, silts, and clay. Brine at 10% weight of the sand is then added and thoroughly mixed with the dry sand. The wet sand is packed inside the test cell following a layer-by-layer technique known as the moist tamping method [23] to ensure a uniform porosity and permeability distribution along the sand pack. Once the sand-pack reaches the top, the top platen is installed, and the load piston applies 60 psi of axial stress. Next, the sand pack is saturated from bottom to top at a low flow rate to avoid permeability damage in the sample.

The absolute permeability of the sample is measured before brine displacement by oil. Three differential readings across the sample confirm an even permeability. Oil is injected from the sample top towards the coupon at 1250 cc/h to displace the brine and reach irreducible water saturation, emulating the reservoir's initial saturation condition [7].

The test includes the injection of single-, two-, and multi-phase flow stages (Figure 5). The duration of each stage depends on the distribution of flowing phases and pressure stabilization to achieve a steady-state flow. Three flow rate levels are designed to account for scenarios like reservoir heterogeneity, aperture plugging, and non-uniform flow distribution. The maximum liquid flow rate (7200 cc/h) corresponds to 4000 bbl/day of liquid production from an 800-m SAGD production well equipped with a 7-inch screen, where only 15% of the well contributes to the flow. The medium- and minimum-flow rates correspond to scenarios where 50% and 70% of the well contribute to the flow, respectively.

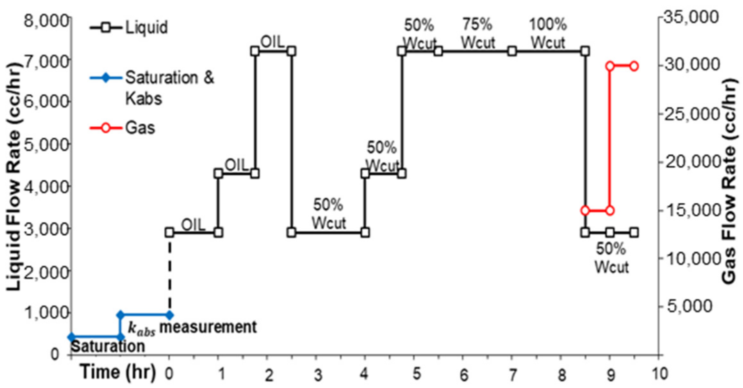


Figure 5. Fluid injection program.

The three single-phase oil stages in Figure 5 emulate sections of the well that produce high oil cuts. Next, the injection of brine and oil captures the changing conditions of SAGD wells, where different liquid rates and water cuts are experienced throughout the wellbore life [24]. The flow scheme includes a single-phase brine stage to account for high water cuts, representing the worst-case scenario for sand production and fines migration [25]. Lastly, two stages of co-injection gas (N_2), brine and oil, resemble the event of steam breakthrough. Although the precise influx conditions during such episodes are not known, the liquid rates are dropped to the initial level (total liquid rate of 2900 cc/h) since it is anticipated that high steam mobility may restrict liquid inflow.

4. Testing Program and Evaluation Method

Cumulative sand production and retained permeability are the sand retention and flow performance indicators, respectively. Produced sand is reported in pounds per square foot (lb/ft^2) of the coupon area. Retained permeability is evaluated after the last liquid stage (100% brine flow) as the ratio of effective permeability at the near-screen zone over initial effective permeability at irreducible oil conditions. The Wang et al. [26] method was used in this study to obtain the retained permeability under multi-phase conditions at residual oil saturation tests (Table 2).

Table 2. Relative permeability at irreducible oil conditions.

Sand Class	k_{abs} (md)	k_{rel} (Fraction) at S_{or}
DC-I	950	0.48
DC-II	1800	0.52
DC-III	2400	0.54

5. Testing Results

5.1. Sand Retention Performance

WWS's ability to retain the production of solid particles relies on the stability of particle bridges, which is mainly controlled by the ratio of the aperture size over the particle diameter [27], local fluid velocity [28], grain shape [29], water cut [25,30], and flowing phases [7].

This study established sand production limits at 0.12 lb/ft^2 for moderate sanding and 0.15 lb/ft^2 as the upper threshold for cumulative sanding. These limits correspond to limiting cumulative sand to less than 1% of the liner volume [31]. Similarly, Hodge et al. [32] correlated laboratory performances with field data and proposed a value of 0.12 lb/ft^2.

Figure 6 shows negligible sand production during the oil stages for all sand classes, which can be attributed to the strong capillarity bonding between grains. Even at high oil flow rates and wider slots, minimal sanding is observed. After the water breakthrough, more sand production is expected due to the reduction of the capillary bonding force. However, for 0.006″ and 0.010″ coupons in DC-III, there is minimal sanding even after water breakthrough, indicating stable sand bridges are formed on the small apertures that could provide a strong capability to prevent sand production. However, wider slots exhibit transient sanding. In transient sanding, some sanding is observed upon changing the flow rate or water cut, with the rate eventually declining until stable bridges are formed at constant flow rates.

Increasing flow rates induce higher pressure gradients through the sand bridges, and the drag forces can exceed the frictional resistance of the bridge. The impact of flow rate fluctuations is more substantial for wider slots, since greater aperture size to grain size results in weaker sand bridges.

Transient sanding was also observed during the co-injection of brine, oil, and gas, but at more intense levels. Interestingly, gas–liquid flow can destabilize the bridges, even over narrow apertures such as 0.006″. Wider slots (>0.014″) displayed significant sand production. In cases like the 0.018″ test for DC-I, bridge stability is never achieved, and particles are continuously produced, known as continuous sanding.

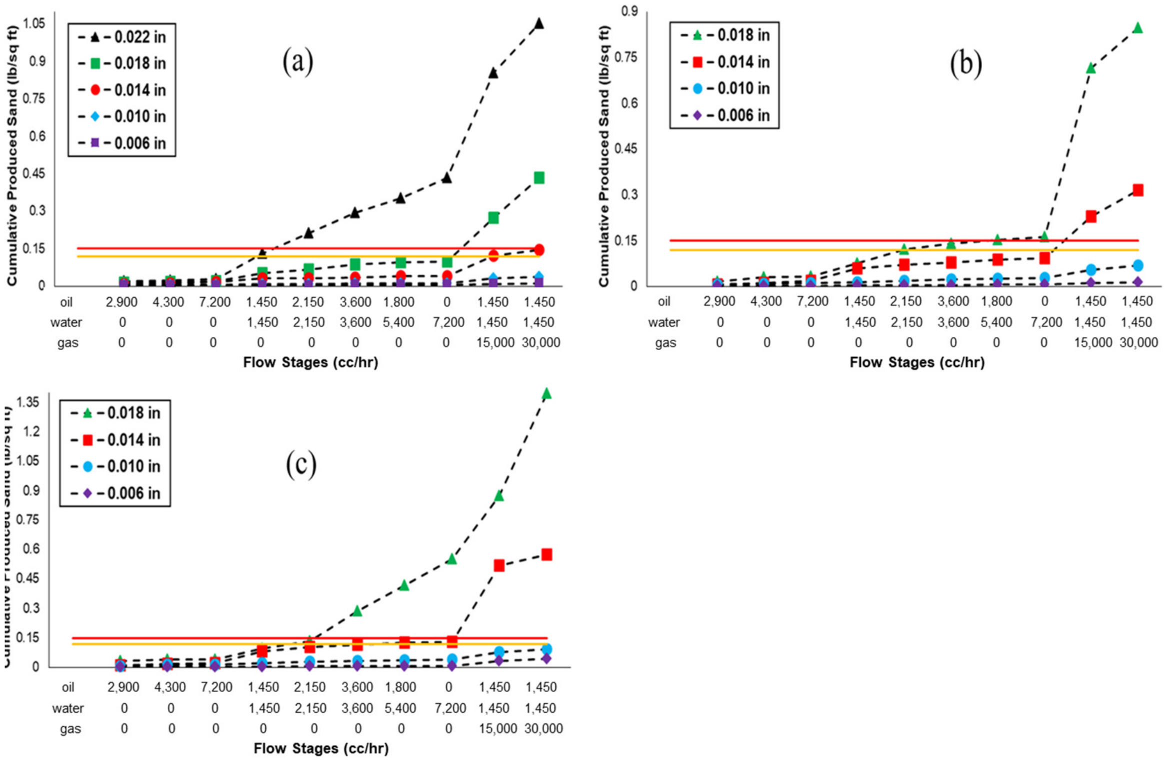


Figure 6. Cumulative sand production; (**a**) DC-III, (**b**) DC-II, (**c**) DC-I. Red and yellow horizontal lines represent the sanding limits of 0.15 lb/ft^2 and 0.12 lb/ft^2, respectively.

5.2. Flow Performance

The retained permeability normalizes the final permeability of the near-screen zones against the initial permeability. This parameter allows for a better comparison of the flow performance of different sand control designs. Effective retained permeability determination uses the relative permeability values ($k_{rw@Sor}$) from Table 2 and the pressure drop reading from the last liquid stage:

$$k_{ret} = \frac{k_{w,bottom}}{k_{abs} k_{rw\ @S_{or}}}$$

$$k_{w,bottom} = \frac{q_w \mu_w L_b}{\Delta P_b A}$$

where $k_{rw@Sor}$ is the relative permeability to water at residual oil saturation, $k_{w,bottom}$ is the final effective permeability after the last liquid stage, and k_{ret} is the retained permeability. ΔP_b is the pressure drop at the bottom section of the sand-pack. q_w and μ_w represent the water flow rate and viscosity, respectively.

Burton and Hodge [33] analytically found that a negligible impact on productivity occurs for retained screen permeability above 20% due to the high permeability of the screens compared to that of a porous medium. Later, retained permeability of 50% in the near-wellbore region was proposed to account for other formation damage sources [12,32]. This study considers 50% and 70% for the marginal and acceptable limits of retained permeability, respectively.

Figure 7 displays the retained permeability as a function of aperture size for the three sand classes. As expected, the fines can easily be dislodged from the sand-pack for the wider aperture size, resulting in minimal plugging. Remarkably, WWSs provide retained permeability values above 50%, even for narrow apertures such as 0.006″ in low-quality sand, i.e., DC-I. In DC-III, increasing the aperture size beyond 0.018″ does not further improve skin but results in higher sanding levels. Flow performance decreases from DC-III to DC-I, as narrow pore throats are prone to plugging.

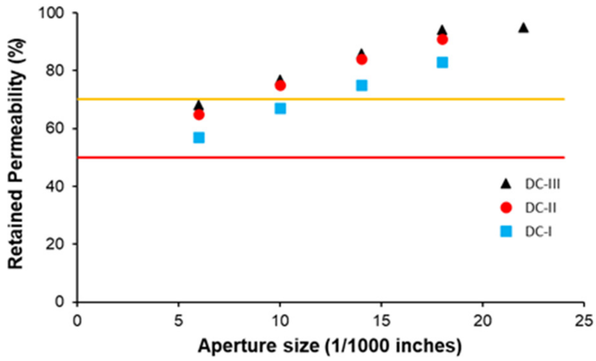


Figure 7. Retained permeability for different aperture sizes and sand classes. The red and yellow lines represent the retained permeability limits of 50% and 70%, respectively.

6. Design Criteria for WWS

Flow and sand production performances obtained with the SRT are combined to elaborate a set of graphical design criteria for WWS. The proposed criteria specify an aperture size window that keeps the produced sand within an acceptable limit while minimizing plugging potentials and maintaining wellbore productivity. Unlike previous criteria, the criteria introduced here differentiate production scenarios to evaluate their influence on the safe aperture zone. The optimum aperture window provides an upper bound and a lower bound. The upper bound is governed by sand production performance, while the flow performance dominates the lower bound.

6.1. The Traffic Light System (TLS)

The TLS is a graphical approach to rank the performance of different aperture sizes for specific sand classes proposed by Wang et al. [34] for slotted liners. This paper uses the same procedure for WWS. The performance is presented on an axial representation of the PSD (Figure 8) that contains representative D-values along the axis (red lines) as well as the aperture sizes implemented in the testing (dashed lines). The performance limits are used to categorize the response of WWS as acceptable, marginal, and unacceptable for sand retention and flow performance. Table 3 presents the color definitions for each indicator.

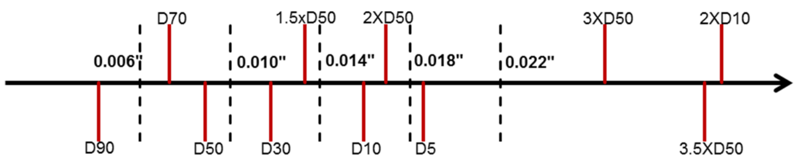


Figure 8. Example of linear *x*-axis representation of the PSD for DC-III.

Table 3. TLS color code.

Color Symbol and Description	Sand Retention Performance for Cumulative Sand Production	Flow Performance by Retained Permeability
Unacceptable	More than 0.15 lb/ft^2	Retained permeability less than 50%
Marginal	Between 0.12–0.15 lb/ft^2	Retained permeability between 50–70%
Acceptable	Less than 0.12 lb/ft^2	Retained permeability less than 50%

6.2. Design Criteria

The criteria differentiate two production scenarios, including regular and aggressive SAGD conditions. Experimental results up to the last liquid stage represent a regular SAGD case where a well exhibits changes in flow rate and water cuts throughout its life. The aggressive flow, defined as the flow during the three-phase flow condition, represents the steam breakthrough (see Figure 5). SAGD operators strive to identify "hot spots" and control these events due to their impact on the steam-chamber growth efficiency and risks of liner damage.

Figure 9a,b show an example of the axes for sand retention and flow performance for DC-III, respectively, under regular conditions. Combining both performance indicators generates the optimum aperture window (Figure 9c). The same method is used to create the final aperture size window for DC-II and DC-I under regular SAGD conditions (Figure 10). The safe aperture window narrows down from DC-III to DC-I. Fine sands produce more solids, requiring the implementation of smaller apertures. However, smaller apertures promote pore and slot plugging, reducing the range of optimum sizes.

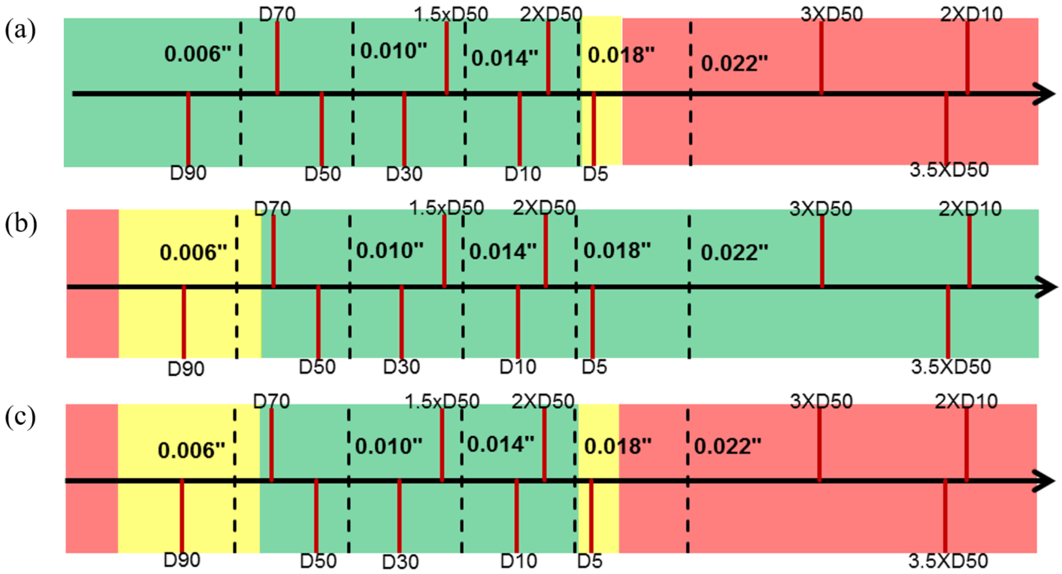


Figure 9. Aperture window for DC-III for regular SAGD conditions (red: unacceptable, yellow: marginal, green: acceptable); (**a**) sanding performance, (**b**) flow performance, (**c**) overall design window.

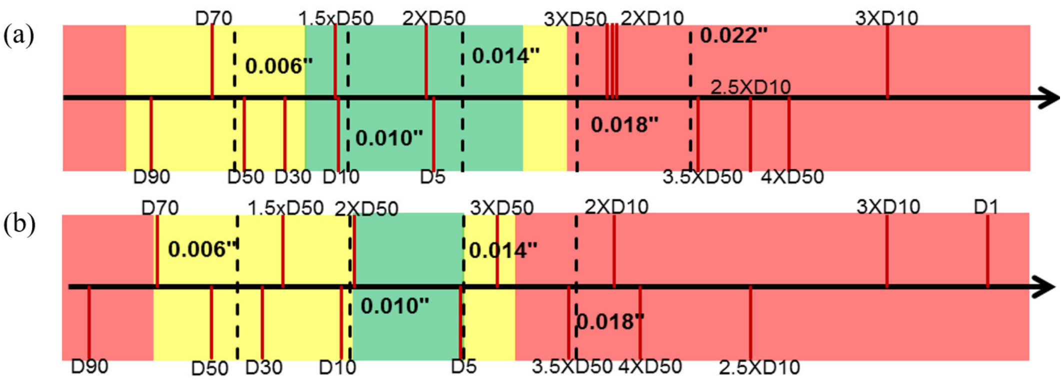


Figure 10. Overall aperture window in regular SAGD conditions (red: unacceptable, yellow: marginal, green: acceptable): (**a**) DC-II, (**b**) DC-I.

Figure 11 presents the TLS design criteria for the samples in aggressive conditions (during steam influx). By comparing the TLS criteria for regular and aggressive flow situations, it is evident that the aperture window shrinks for the aggressive condition. The reason is high levels of sanding due to strong drag forces during gas flow, shifting the upper bound to the left.

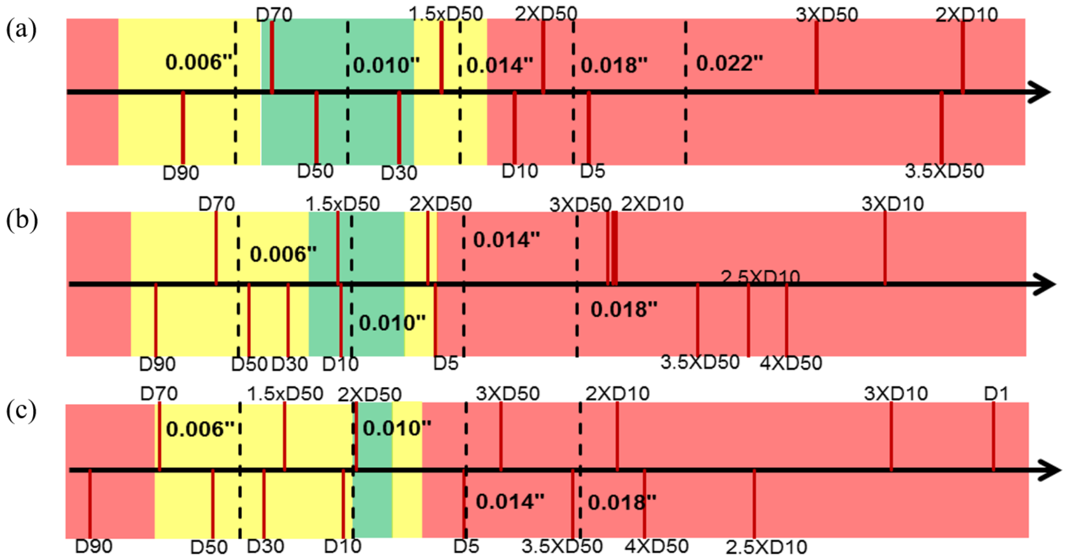


Figure 11. Overall aperture window in aggressive SAGD conditions (red: unacceptable, yellow: marginal, green: acceptable); (**a**) DC-III, (**b**) DC-II, (**c**) DC-I.

In summary, the high OFA of WWS results in low pressure gradients and high fines discharge that reduce pore plugging potential. As a benefit of high OFA, WWS allows the selection of narrow apertures that can handle a wide range of PSDs. However, for coarser sands, selecting narrow apertures may diminish the advantages of high OFA. Furthermore, the TLS shows how the adequacy of current criteria (i.e., D10, 2D50) is highly dependent on production scenarios, and that such simple criteria do not work consistently for all PSDs. Therefore, the graphical design criteria are created for each sand class, accounting for the entire shape of the PSD curve and the operating conditions.

7. Discussion

This paper presents the performance of WWS through an experimental study by including several key parameters, such as flow rate, water cut, PSD, and aperture size. Based on the sanding and flow performance, the aperture design criteria are generated for different SAGD operation conditions, which could provide some guidance to the field engineers in selecting the proper aperture size.

It should be mentioned here that there are more influential factors in the testing design that are not investigated in this study, such as temperature, paraffin deposition, etc. [35,36]. Thus, additional testing scenarios and field data are required to validate and calibrate the proposed aperture design criteria.

8. Conclusions

This research introduces design criteria for WWS in SAGD applications, considering the role of operational scenarios, flow rate, PSD, and aperture size on the screen performance. The results show that production scenarios strongly influence sanding intensity; wider slots exhibit extreme sanding levels during steam-breakthrough stages but respond reasonably well during liquid stages. Drag forces play a critical factor in disrupting particle bridges. A positive conclusion for WWS is that the retained permeability values stay above acceptable limits (50–70%), even for finer sands. WWS displays a substantial ability to release fines.

Sanding and flow performance results are combined to determine optimum-aperture windows for three sand classes using the TLS approach, incorporating PSD and production scenarios. Aggressive conditions shrink the safe-aperture window compared to normal SAGD conditions, which signifies the influence of operational practices in the performance of screens. Elevated flow rates and steam production significantly impact sanding and plugging and must be considered in aperture size design. For instance, for low sub-cool levels, the risk for the steam influx is more eminent, and the effect of aggressive conditions would affect the aperture sizing selection.

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Abbreviations

OFA	Open-to-Flow Area
PS	Punched Screens
PSD	Particle Size Distribution
SAGD	Steam Assisted Gravity Drainage
SAS	Standalone Screens
SCD	Sand Control Devices
SL	Slotted Liner
SRT	Sand Retention Test
TLS	Traffic Light System
WWS	Wire-Wrapped Screen

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