Erosion of sand screens by solid particles: a review of experimental investigations

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Abstract

In oil and gas industry, sand can be carried with oil and gas, when producing from unconsolidated sandstone reservoirs. The existence of sand particles with fluids flow can lead to severe damages to production system's components. Therefore, sand control techniques are needed to prevent potential damages. Standalone sand screens (SAS) are widely used because they can provide reliable sand control with low cost and low complexity. However, SAS application can become disadvantageous because of mechanical erosion due to sand particle impingement. The experimental investigation of sand screens erosion is challenging, as the measurements are to be carried out for a representative SAS material and geometry at laboratory-scale simulated conditions. The simulated conditions should mimic the real flow conditions, which involve many interrelated parameters. Some of these parameters are related to the entrained sand particles (i.e., particle shape, size and, concentration) while other parameters are related to the flow characteristics (i.e., flow velocity and fluid properties). In this review, the key factors influencing sand screens erosion are described, and erosion mechanisms are highlighted. In addition, experimental results showing the effects of key parameters on SAS erosion are discussed and evaluated. Also, challenges associated with previous studies, along with a proposed outlook to overcome those challenges, are presented. It has been found that the limitations of the previous studies are related to test setup and flow direction, particle–particle interaction, and particle–fluid interaction considerations. This review highlighted noticeable research gaps in sand screens erosion measurements that can be considered in future.

Keywords Sand particle erosion · Erosion mechanism · Screen erosion · Stand-alone screen · Erosion modelling

Abbreviations

SAS	Standalone screen
PSD	Particle size distribution
ESS	Expandable sand screens
WWS	Wire wrapped screen
MMS	Metal mesh screen
MWM	Metal wire mesh
UC	Uniformity coefficient

SC	Sorting coefficient
DOE	Design of experiment
SE	Specific erosion

List of symbols

D90	Sieve opening size that retains 90% of the particles
D70	Sieve opening size that retains 70% of the particles
D50	Sieve opening size that retains 50% of the particles
D10	Sieve opening size that retains 10% of the particles
$\bar{d}$	Mean diameter, m
n	Spread parameter
α	Particle concentration
d_{50}	Median size of sand, μm
D	Scree size, μm
St	Stokes number
τ	Particle relaxation time
U	Velocity of fluid

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L	Characteristic length
θ	Impingement angle

Introduction

During production of oil and gas from sandstone reservoirs, particularly from loose and mature formations, solid sand particulates may be disattached from the bulk rock and entrained with the produced fluids. While moving, the produced sand may impact the internal surfaces of the pipes and production components, causing material wear (i.e., mechanical erosion). If not detected early and alleviated, sand erosion may lead to hydrocarbon leakage from piping components and total failure of other production facilities such as pumps, compressors, and valves. The industrial practice for minimizing or avoiding sand production, and hence sand erosion, is by implementing sand control techniques, such as mechanical sand control (Ma et al. 2020; Wu et al. 2016) and/or chemical sand control (Alakbari et al. 2020).

There are many sand control techniques applied at different locations for different types of fluids which resulted in controlling sand production to different extent of success. However, there is no specific sand control method that can be successfully applied for all types of unconsolidated sandstone reservoirs (Ben Mahmud et al. 2020). Nonetheless, mechanical sand screen is the sand control method most widely used due to its simplicity and low cost. The simplest scenario of applying sand screen is to use it as a standalone (without gravel pack). The standalone screen (SAS) can effectively minimize sand production by retaining sand particles with a specified size in the formation and hinder sand entrainment with the produced fluids. However, SAS itself is frequently susceptible to sand erosion, which may affect its efficiency, and in the worst cases, the screen may totally fail to perform sand control (Nizar Musa et al. 2017; G. K. Wong et al. 2003). Therefore, the degree by which SAS undergoes erosion at expected operational conditions and reservoir characteristics must be examined as part of sand control design. The best way to achieve that is by measuring SAS erosion rate inside laboratories using sand and fluids samples that represent those of the reservoir, where the screen is intended to be used. For a proper testing results, the real reservoir conditions and flow characteristics need to be mimicked while conducting the measurements. Also applying a representative flow orientation is a key factor that may need a special laboratory setup and careful execution of tests. In the literature, there are many attempts of conducting experimental testing of different types of SAS at wide ranges of flow and sand characteristics.

This current paper reviews previous experimental studies, over the past fifteen years, and highlights how the key factors affecting SAS erosion are examined. The paper starts

with explaining the mechanism of screen erosion and then discusses the effect of the parameters related to flow, sand, and material on SAS erosion. This review focuses on the essential factors affecting solid particle erosion which most of the studies focused on. The reviewed factors are impact velocity, impact angle, particle size distribution and concentration effect, and carrier fluid type and properties. Firstly, the parameters are defined, and then, the experimental studies which focused on them are discussed and compared in terms of findings, ranges, and experimental consideration. Parameters effects on erosion are presented and compared in a form of graphical presentations that show the typical trend of the effect of every parameter. At the end of the paper, based on the limitations of previous experimental attempts, future outlooks and proposed pathways are summarized as recommended guidelines to researchers.

Mechanism of screen erosion

A review of some of the proposed mechanisms of sand screen erosion will be discussed in this section. Zhang et al. (2020) suggested that small particles affect the filtering layer after passing through the gravel layer. Turbulence causes irregularity and collisions with the filtering layer at various angles and velocities, which can lead to extrusive lip or depression and can even produce radial cracks. Subsequently, the material will be peeled off if the impact force is large enough. Moreover, they stated that, ‘sand screen erosion is a process where a huge number of discrete particles erode a screen at multi-angle in the turbulent regime’. Other studies such as those conducted by Greene and Moen (2012) and Regulacion and Shahreyar (2011) found that annular flow plays an essential role in the erosion and failure of sand screens in horizontal gas wells. However, Gillespie et al. (2009) attributed early life failures of the screen to severe plugging with solids in a drilling fluid, which could have occurred during installation. Therefore, if a well is made operational, the increased flow could cause highly localized entrance velocities towards the screen. Consequently, screen may fail in a short time depending on the flow rate, the degree of screen plugging, and the concentration of transported fines. It should be highlighted here that the relationship between velocity and erosion rate is very strong such that even a relatively small increase in fluid velocity can have a huge impact on the specific erosion so much so that a 50% increase in fluid velocity can increase the specific erosion by as much as 170% (Greene and Moen 2012). In addition, some studies such as (Abduljabbar et al. 2021) found that the existence of high fine content can result in a considerable increase in erosion rate as flow velocity increases.

As far as the issue of plugging is concerned, Hamid and Ali (1997) suggested that the screen erosion mechanism is

due to partial plugging, which happens in the presence of a mixture of coarse sand particles and fines. Furthermore, they added that depending on the particle size distribution (PSD) of the gravel, partial plugging may happen with or without full annulus packing. There are other authors who highlighted the mechanisms of screen erosion such as Sveta et al. (2009). They identified two mechanisms of screen erosion: (1) screen plugging with scale or fines, which results in intense flow through a small portion of the screen with consequent erosion and failure, and (2) fines mobilization and sand/fines production associated with water breakthrough, which results in screens erosion. Regarding screen plugging, according to Procyk et al. (2015), although screen plugging is anticipated under normal field conditions, for erosion test purposes, using a small and constant-sized particle slurry provides more reliable long-term erosion results and improves test repeatability. Thus, to prevent plugging during testing, they sieved the particle size to 32 μm average diameter. From the above statements, plugging can be considered as a factor that provokes erosion as it will create high-velocity spots. However, studies about the plugging-induced erosion of sand screens are very limited. Therefore, the mechanism of erosion in this case should be understood and examined.

Essential factors affecting solid particle erosion

Erosion of sand screens is a progressive failure that depends on the velocity of fluid flow, size of sand particles and their concentration, angle of incidence, flow duration and properties of fluid (such as viscosity and density) (Procyk et al. 1998). Several experimental studies had been conducted to examine the effects of various factors on the erosion of different types of sand screens as will be discussed in the following sections.

Impact velocity

During sand screen erosion experiments, flow velocity is changed such that the effect of impact velocity can be quantified and analysed. For instance, the following studies considered changing the velocity during experiments, Deng et al. (2019a), Kanesan et al. (2019), Kumar et al. (2018), Procyk et al. (2015), Gillespie et al. (2009), Liu et al. (2009), Cameron and Jones (2007) and Hamid and Ali (1997). Conversely, few studies considered constant flow velocity during experiments, such as McKeon et al. (2017) and Charles and Fipke (2017). The impact velocity of solid particles is a very significant parameter contributing to the erosion of impacted surfaces. For a given sand concentration, the most important parameter is the velocity (Greene and Moen 2012). The

effect of the velocity will dominate and significantly change the erosion magnitude. Moreover, according to D. Kumar et al. (2018), the erosion risk of sand screens when entrained solids are carried by fluids, the key factor controlling erosion is the velocity. An observation by several studies on the erosion phenomena is that there is a critical velocity above which the erosion starts and then increase. Therefore, due to the significance of impact velocity, several experimental studies aimed to quantify its effect under various conditions.

In this section, studies on sand screen erosion will be reviewed with regards to velocity, in terms of velocity ranges during experiments, the mathematical relationship type between erosion and velocity, particle velocity relation with carrier fluid velocity, and fluid/particle velocity correction. Regarding the studies which considered the effect of changing the velocity, their experiments have been conducted under a wide range of velocities, from low velocities (such as Cameron and Jones (2007), Gillespie et al. (2009) and Procyk et al. (2015)) to high velocities of up to 190 m/s (such as the experiment conducted by Kumar et al. (2018)). Kumar et al. (2018) justified that higher air velocity (approximately 10 times) compared to that typically observed in the field had to be chosen such that the test duration is reduced to a few hours. However, Fucheng et al. (2014) revealed that if the fluid velocity is very high during the experiment, the slot will be eroded very quickly, and if the sand content is too high, sand will accumulate on the slot. Consequently, this could result in experimental data that contradict the field data (Fucheng et al. 2014). From the above, it is necessary to select the experimental flow velocity such that it represents the anticipated practical and operational ranges.

Relationship between erosion and flow velocity

As for the relationship between erosion and flow velocity, a general observation is that erosion rate increases as flow velocity increases. However, different mathematical relationships have been observed for various studies. For example, the data of Kanesan et al. (2019) are plotted in Fig. 1, and a linear relationship closely represents the trend. Importantly, note that their set of experiment was conducted under constant particle size of 150 μm at 90° impact angle. On the other hand, Kumar et al. (2018) suggested that, above a critical velocity, erosion increased almost linearly with the velocity. However, if we look at Fig. 2, a nonlinear trend is clear and a quadratic equation shows a better correlation than the linear trend. Kumar et al. (2018) suggested that, below a critical velocity of 70 m/s, the screen did not measurably show erosion. However, as the velocity increases, the increasing trend of erosion is clear through the first three points, and then, the curve shows a downward trend indicating that erosion reduces as velocity increases. There are other studies which examined the effect of velocity under

Fig. 1 Plot of velocity effect on erosion from experimental results at constant particle size of 150 micron and 90° (Kanesan et al. 2019)

constant and variable particle concentrations. For example, Fucheng et al. (2014) expressed the flow change in terms of the pressure difference change and showed that for the slotted screen, the erosion rate exponentially increased with the production pressure difference at a constant sand content, as shown in Eq. 1.

$$ER = 0.2364 \times 10^{-4} e^{0.5137\Delta p} \quad (1)$$

where ER is the erosion rate in mm/s and Δp is the production pressure difference in MPa. On the other hand, an example of the studies conducted under variable particle concentration to examine the effect of velocity is the study conducted by (Procyk et al. 2015). The interesting side of Procyk et al. (2015) study is that the effect of velocity can be analysed together with the change of solid particle concentration, as plotted in Fig. 3. The velocity and concentration data were as follows: 0.18 m/s (592 ppmw), 0.73 m/s (four concentration values: 798, 806, 809, and 849 ppmw),

Fig. 2 Gas velocity effect on the erosion of wire wrapped screen (WWS) $D_{50} = 190 \mu\text{m}$, uniformity coefficient $UC = 2$, sand concentration: $0.3 \pm 0.05 \text{ lbs/min}$, total impinged sand: 25 lbs—reproduced from Kumar et al. (2018)

Fig. 3 Plot of Procyk et al. (2015) data of face velocity effect on woven wire mesh erosion

and 0.98 m/s (762 ppmw). For the purpose of analysis and in order to examine the effect of velocity under different conditions, a plot has been generated using the results from (Procyk et al. 2015) for the above velocities such that the four points of the 0.73 m/s are averaged to represent one data point, as shown in Fig. 4. The trend can be best fitted with power law relationship, as shown in Eq. 2, despite the inconsistent change of particle concentration with increasing velocity (i.e., 592, 815.5, and 762 ppmw, respectively)

$$SE = 2 \times 10^{-5} v^{2.5691} \quad (2)$$

where SE is the specific erosion in g/g and v represent the face velocity. Similarly, from Cameron and Jones (2007) study, a power law correlation has been found between specific erosion and fluid gap velocity corrected for plugging. It is clear, from the above findings, although most of the experimental results show nonlinear relationships, experiments with more data points and variables are needed to establish

Fig. 4 Plot of Procyk et al. (2015) data for face velocity effect with changing particle concentration on woven wire mesh

clear trends. Table 1 provides a summary of experimental studies on sand screen erosion with the effect of velocity.

Particles velocity versus carrier fluid type and velocity

As shown previously, in many studies on solid particle erosion, the effect of carrier fluid velocity on erosion rates had been analysed. Reportedly, the erosion rate increases with the velocity of the carrier fluid. However, the particle velocity may remarkably differ from that of the carrier fluid, particularly if liquid was the carrier fluid. This difference can also be encountered in gas flows.

Mansouri et al. (2014) highlighted that the gas velocity is not the same as the particle impact velocity because of a slip velocity between sand particles and gas. They explained that the velocity of sand particles is slower than the gas velocity. These findings highlight the importance of investigating the velocity effects on erosion under different types of fluids and variable sand concentrations. Some studies considered the effect of velocity on erosion under different carrying fluid types such as the study conducted by Gillespie et al. (2009). They investigated the erosion of two metal mesh screens (MMS), having openings sizes of 135 and 300 micron, where water and glycol (50 cp) were used as carriers fluids. They highlighted that surprisingly, the specific wear rates for water were higher than those for glycol at the same velocity of 0.61 m/s. The above observations highlight the significance of carrier fluid type consideration during erosion testing.

Near wellbore condition effects on fluid and particles velocities

Another consideration regarding flow and particles velocity is the influence of near wellbore condition. Cameron and Jones (2007) explained that for expandable completion, sand moving towards the wellbore from the tunnel directly impacts the screen because of the reduced or minimal annulus. In that case, the tunnel particle/fluid velocity (v_c) will be equal to screen face particle/fluid velocity (v_s). However, the screen approach velocity (calculated volumetrically) needs to be corrected for plugging. The fluid/particle velocity should be corrected with respect to the area open to flow. This corrected velocity is referred to as the ‘gap velocity corrected for plugging’. Hence, the fluid and particles will have high acceleration from the approach to gap velocities. From the figures shown in Cameron and Jones (2007), erosion with liquid occurs at lower velocities than that with gas. They explained this observation by the idea that since the density of gas is low, its ability to accelerate the particles towards the surfaces is low. The observations highlighted by Cameron and Jones (2007) are very important when using erosion prediction equations which are functions of flow velocity and to consider the corrected velocity due to restrictions such as plugging. There could be other considerations for velocity corrections such as multiphase flow and flow regimes around the wellbore which need to be investigated and taken into account.

Impact angle

Impact angle is defined as the angle between the targeted surface and the direction of particle impact velocity. In general, mass loss rate caused by erosion is believed to be a function of particle impact angle (Nandre and Desale 2018) (Venkatraman Krishnan and Lim 2021). However, its effect on erosion depends on the material of the surface. Most of the materials used in oil and gas industry have characteristics of both brittle and ductile materials. The relationship between particle erosion rate and impact angle for brittle and ductile materials is shown in Fig. 5. As clearly shown, the erosion rate trends for brittle materials are quite different from those for ductile materials. As for ductile materials, maximum erosion rates occur at lower impact angles. Conversely, the highest erosion for brittle material occurs at angles near the normal impact angle (90°) since the main cause of erosion of brittle materials is cracking (Parsi et al. 2014; Rameshk et al. 2020; S. Kumar et al. 2008).

In this section, some examples are provided for experimental studies which identified the maximum erosion of sand screens under different impact angles. Then, the dependency of impact angle on the particle’s properties, the carrying fluid, and the interaction between them will be

Table 1 Experimental studies on sand screen erosion with the effect of velocity

Authors	Studied screen	Fluid type	Velocity range (m/s)	Observations
Deng et al. (2019a)	Monolayer metal-mesh screen	Oil	1–10	Erosion rate exponentially increased with velocity The fluid flow velocity decreased as the sand content increases The proposed erosion rate relationship includes flow velocity: $\lambda_e = 0.0107v^{1.316}\alpha^{0.721}\left(\frac{d_{50}}{D}\right)^{0.286}(1 - 3.454\alpha)$
Kanesan et al. (2019)	Wire-mesh screen coupon	Air	74.58 33.46 19.81	Erosion increased as the velocity of carrier fluid increased
Kumar et al. (2018)	Wire-wrapped screen	Air	70–192	- Below a critical velocity of 70 m/s (230 ft/s), the screen did not measurably erode, but above the critical velocity, the erosion increased almost linearly with the velocity
Procyk et al. (2015)	Woven wire mesh	Water	0.18 0.73 0.98	The relationship between specific erosion and velocity is a power law function of velocity (Vn) The tested screen had higher specific erosion rate as a function of inlet flow velocity than other tests in literature (135 μ m screen; Cameron, 2007) and those previously tested internally (85 μ m screen)
Gillespie et al. (2009)	Wire-wrapped and metal mesh	Water and glycol (50 cp)	0.122–0.61	The wear rates of the WWS were generally less than that of MMS For water: at 0.61 m/s (2 ft/s), the specific wear for WWS was approximately 60% of the MMS 300 rate and approximately 73% of the MMS 135 rate. However, wear rates were approximately the same at 0.15 m/s (0.5 ft/s) For glycol: at 0.61 m/s (2 ft/s), the ratios were different as the specific wear of WWS was 41% of the MMS 200 rate and the WWS was approximately 73% of the MMS 135 rate. Moreover, these ratios were approximately the same for the WWS and MMS 200 at 0.15 m/s (0.5 ft/s)
Cameron and Jones (2007)	Expandable sand screens (ESS)	Water and gas	0.168–~6.1	A power-law relationship between specific erosion and fluid velocity Observed clear effect of particle/fluid interaction and highlighted that further study is ongoing to evaluate screen erosion using fluids with higher density/viscosity

discussed. Fluid type effects and experimental setup with respect to impact angle are also highlighted.

Maximum erosion of sand screens under different impact angles

There are some studies on sand screen erosion which considered the effect of impact angle. For example, Liu et al. (2009) experimentally examined the erosion of slotted screen by considering the impact angle in addition to the flow velocity of crude oil, sand particle diameter, and concentration. They found the maximum erosion rate occurred at 90° angle of impact. They concluded that this behaviour was different from the erosion wear mechanism of plastic materials. Another example is the study conducted by Kanesan et al. (2019) on wire mesh sand screens using

sand blasting technique. Sand blasting is an abrasive technique process widely used for various objectives of surface materials testing (Jianxin et al. 2007). Kanesan et al. (2019) tested the erosion at four different impact angles (30°, 45°, 60°, and 90°) as shown in Fig. 6. They found that the highest erosive wear occurred at 45°, which is consistent with the trend found by other studies for ductile metals such as (Al-Bukhaiti et al. (2007), Divakar et al. (2005), Nguyen et al. (2014)). Kanesan et al. (2019) thought that this finding might be utilized as a base for completion designs for deviated wells so that extra reinforcement is considered for wells deviated at a 45° angle, which would be exposed to maximum erosion.

Fig. 5 Erosion rate for different materials against particle impact angles; particle impact velocity is 153 m/s. Silicon Carbide Grit: **a** brittle and **b** ductile [reproduced from Sheldon (1970)]

Fig. 6 Plot of experimental results of erosion at different particle size and impact angle (Kanesan et al. 2019)

Fluid type and experimental setup considerations with respect to impact angle

As shown earlier that the erosion magnitude is a function of impact angle, it is of great significance to highlight that the solid particle impact angle itself depends on the particle's properties, the carrying fluid, and the interaction between them. According to Zhang et al. (2020), most erosion models for screens deal with all sand as a whole, whereby different angles of impact of each particle are not considered. Therefore, the process of erosion at a variety of angles in the turbulent flow region cannot be precisely

described. Zhang et al. (2020) concluded that sand particles are influenced by the turbulent flow out from the perforation tunnel or the formation pores and that sand particles impinge the screen wire at different angles and velocities, resulting in continuous wearing until total erosion damage occurs. One of the indicators of flow influence on particle trajectory is given by the Stokes number, defined as $St = \tau U/L$ (where τ represents the particle relaxation time, U is the velocity of fluid, and L represents the characteristic length). Many erosion experiments are conducted under dry conditions (i.e., sand particles in gas/air) wherein Stokes numbers are high. In that condition,

the particle's inertia is dominant and fluid flow influences on particles trajectories are ignored, implying that particle's local impact angle (α) is the same as the jet impingement angle (θ). According to Mansouri et al. (2014), this enables investigators to control the particle impact velocity and angle during gas–solid testing. On the other hand, for slurry flows wherein the liquid viscosity is significantly higher than that of gas, the relaxation time of particles significantly decreases. Therefore, in slurry flows having low Stokes numbers, sand particles tend to follow the fluid streamlines and the fluid flow causes curvature in particle trajectories prior to impact. Hence, particles impact the surface at various ranges of impact angles and speeds, as shown in Fig. 7.

Having identified the variations in the impact angles depending on the fluid used, some examples of erosion studies on sand screens, with regard to fluid type, are given here. Several studies used air and/or gas during tests, such as Kanesan et al. (2019), Kumar et al. (2018) and Zamberi et al. (2014). Conversely, studies such as McKeon et al. (2017), Charles and Fipke (2017), Procyk et al. (2015), Zamberi et al. (2014) and Gillespie et al. (2009) used water as the carrier fluid. However, few experimental studies used viscous fluids to study the erosion of sand screens, such as Deng et al. (2019a) and Liu et al. (2009), in which oil was used, and Gillespie et al. (2009), in which glycol was used. Therefore, the results of each study, according to the fluid used, should be considered if modelling and prediction are to be conducted for fluids other than the tested fluid.

From the above description, we can infer that the erosion test setup and orientation play an essential role in simulating the erosion behaviour of materials under different flow conditions. Experimental setups for sand screen erosion studies can have various orientations and dimensions. For

instance, Deng et al. (2019a), Kanesan et al. (2019), McKeon et al. (2017), Procyk et al. (2015), Gillespie et al. (2009) and Cameron and Jones (2007) conducted erosion tests on circular coupon samples of a particular type of sand screen. Conversely, some experiments were conducted on cylindrical samples, either vertically such as those by Kumar et al. (2018) or horizontally such as those by Charles and Fipke (2017), Zamberi et al. (2014) and Hamid and Ali (1997). Test geometry and orientation are very essential factors that affect the impact angle of solid particles during experiments. Wong et al. (2010) highlighted the importance of the distribution of flow around the wellbore and considered the effect of the deviation angle on screen erosion. They proposed a cylinder in a pipe test, in a configuration shown in Fig. 8, which also shows the cylinder angle β and impact angle α . This testing method is advantageous for examining the effect of erosion through a wide range of impact angles in a single test. Moreover, this setup can be used to simulate sand screen erosion under wellbore conditions given that the geometry is cylindrical, and the impact might not always be normal, but can take various angles.

Recently, Zhao et al. (2019) conducted simulations using finite element method to study the anti-erosion behaviour of materials with patterned surfaces impacted by particle. Their results showed that the erosion rates versus the effective impact angle for their designed surface structures were fairly different from the erosion rates for the flat surface. In addition to the test setup significance regarding erosion, the setup is also significant for studying the performance of sand screens. For instance, according to Haftani et al. (2020), existing testing devices are designed for linear flow regimes. Nevertheless, they stated that the flow around steam-assisted gravity drainage (SAGD) production wells is not linear but radial. They introduced a full-scale completion test facility

Fig. 7 CFD simulation of fluid streamlines and particle trajectories for half of a direct impinging jet. **a** Air flow streamlines, **b** particle trajectories corresponding to air flow, **c** liquid flow streamlines and **d** particle trajectories corresponding to liquid flow [recreated from Mansouri et al. (2014)]

Fig. 8 Cylinder in pipe tests [recreated from Wong et al. (2010)]

to match the radial-flow condition, utilizing a cylindrical-shaped screen instead of disk-shaped coupons. From the above, the erosion test setup and orientation play a significant role in simulating the erosion behaviour of materials.

Sand particle size distribution and sand concentration

Particle size distribution (PSD) and sand concentration are essential parameters as far as erosion is concerned. Screen erosion is normally not an instantaneous failure. It becomes obvious when there is a steady increase in the concentration and size of sand until the amount turns out to be damaging to production (Rawlins and Hewett 2007). PSD presents an indication of the sorting of sand particles and denoted their distribution pattern, as shown in Fig. 9. We should highlight here that sand screens are designed based on the analysis of produced samples and their PSD. However, PSD might not be fully representative and could change with time as production progresses. This point is essential because erosion is affected by the size of the particles that impinge the surface. Thus, in this section, different aspects related to PSD and sand concentration will be reviewed and discussed.

The determination of whether a particle size is erosive is very critical. Fine particles sometimes do not contribute either to erosion or to plugging as they pass freely through the screens. However, reportedly, erosion of wire wrapped screen (WWS) was due to the passage of fine particles across the screen at high velocities (Hamid and Ali 1997). Furthermore, Kumar et al. (2018) found that poorly sorted sand with high fines content causes more erosion damage to the sand screen than uniform well-sorted sand. Conversely, sand below 50 μm has been found to be non-erosive (Hamid and Ali 1997; Agunloye and Utunedi 2014). Therefore, examining the erosion tendency of particles over a wide range of sizes under various conditions is important.

Fig. 9 Examples of sieve analysis: (1) uniform sample; (2) non-uniform sample; (3) gas well off-shore, depth 628 m; (4) gas well off-shore, depth 850 m and (5) oil well, depth 875 m, detail 'A' difference in curve for dry sieved and laser particle size distribution for the same sample (Matanovic et al. 2012)

Effect of particle size and particle size distribution on screen erosion

Several studies had been conducted to investigate the effect of PSD on sand screen erosion. The following studies considered different PSD during their erosion experiments: Deng et al. (2019a), Kanesan et al. (2019), Kumar et al. (2018), Zambari et al. (2014), Gillespie et al. (2009), Liu et al. (2009), Cameron and Jones (2007), and Hamid and Ali (1997). However, studies such as McKeon et al. (2017), Procyk et al. (2015), and Cameron and Jones (2007) considered one or constant PSD. Other studies such as Deng et al. (2019a) considered constant and changing PSD during experiments. Some of the studies on sand screens and their findings on the PSD effect are highlighted and summarized in Table 2. The study by Cameron and Jones (2007) used coarse and fine grits. Although the tests were conducted for different screen types (which makes the comparison less sensible), the coarser grit showed higher percentage of mass loss than fine grits.

Several studies found that as the particle size increases, erosion increases and then decreases after a certain peak value is reached. Kanesan et al. (2019) and Deng et al. (2019a) observed such phenomena for sand screens for monolayer metal wire mesh (MWM). The increase in erosion with increasing particle size had been reported previously by Bahadur and Badruddin (1990), Bitter (1963), Brown et al. (1983), Feng and Ball (1999), and Finnie (1960). Liebhart and Levy (1991) and Tilly (1973) reported a critical size after which the erosion rate insignificantly increases as the particle size increases. Kumar et al. (2018) claimed that the damage severity increases with UC. However, the provided figure does not show such relationship. In addition, the relation of the effect of velocity with sand concentration

Table 2 Experimental studies on sand screen erosion with PSD

Authors	PSD	Observations
Deng et al. (2019a)	160/200, UC = 1–3 D ₅₀ = [35, 94, 120, 153, 212] μm	As the particle size increases, erosion of the metal wire mesh (MWM) increases and then decreases after a peak value is reached The erosion rate shows an exponential relation with particle size
Kanesan et al. (2019)	[150, 450, 700] μm	The erosion wear increases with the particle size The rate of erosive wear gradually decreases as the particle size increases
Kumar et al. (2018)	Sand#3: UC (D40/D90) = 1 Sand#6: UC = 2 CBS-2: UC = 4	Poorly sorted sand with more fines showed more damage than well-sorted uniform sand
Zamberi et al. (2014)	Coarse and fine PSD	In relatively high fine contents system, annular flow will transport the fine particles towards the heel and cause screen plugging at the areas of screen influx, which will subsequently cause hot spots for erosion
Gillespie et al. (2009)	#200 Grit (coarse): [D10 = 63, D50 = 42, D90 = 27] μm #360 Grit (fine): [D10 = 43, D50 = 26, D90 = 14] μm	The coarser grit was used on 300 μm metal mesh screen (MMS) The finer grit was used on the 200 μm and smaller MMS

was not considered. As the effect of the particle size is now known, it is interesting to observe the mathematical relationship between erosion rate and particle size. Deng et al. (2019a) found a relationship for monolayer MWM, as shown in Eq. 3.

$$\lambda_e = -9e^{-5}d_{50}^2 + 0.027d_{50}0.2329 \quad (3)$$

where λ_e represents erosion rate and d_{50} represents middle particle size of sand. However, this relationship represents the condition of constant particle concentration and constant flow. Therefore, this relationship should be examined under other changing parameters, which represents the reality during sand production with reservoir fluids. Conversely, a study on woven and wire wrap screens, Bennett and Svedeman (1998), showed a power-law relation between specific erosion rate and particle size for different screen types.

Note that some experiments were conducted under sieved or constant PSD for test operational considerations. For example, according to Procyk et al. (2015), although screen plugging would be expected under normal field conditions, for erosion test purposes, it was found that using a small and constant-size particle slurry provided more reliable long-term erosion results as well as improved test repeatability. Therefore, to prevent screen plugging, the particle size range for Procyk et al. (2015) study was sieved to a 32 μm average diameter and 90% of the solids' mass was within 15–55 μm range. Similarly, most of the erosion testing on woven and wire-wrap screens by Bennett and Svedeman (1998) was conducted with a 37 μm silicon carbide (SiC) grit. It was chosen as it passed through most screens with no remarkable plugging or otherwise getting trapped in the weaves. From these examples, it is obviously difficult to sometimes simulate experimentally as some challenges are posed that could

require additional sophisticated experimental techniques. Furthermore, Procyk et al. (2015) recognized the possibility of screen plugging occurrence although they did not study it. Therefore, the plugging-induced erosion is one of the areas that requires further studies and simulations.

Effect of sand concentration on screen erosion

To study the effect of sand concentration, some studies considered changing it during experiments, such as Deng et al. (2019a), Kumar et al. (2018), Zamberi et al. (2014), and Hamid and Ali (1997). Although particles concentration is an important factor and naturally changes in reality from field observations, some studies were conducted for a particular constant concentration, such as Deng et al. (2019a), Kanesan et al. (2019), McKeon et al. (2017), Charles and Fipke (2017), Procyk et al. (2015), Gillespie et al. (2009), and Cameron and Jones (2007). The data of Procyk et al. (2015) have been plotted to show the effect of particle concentration at a constant flow velocity, as shown in Fig. 10. The figure depicts that the specific erosion increases with the particle concentration. However, if more data points were available, a clearer trend would have been observed and more information would have been revealed. For WWS, Kumar et al. (2018) found that increasing sand concentration yielded higher erosion. Deng et al. (2019b) found that as the sand concentration increased, the erosion of MWM initially increased and then decreased after a peak value was reached. For slotted screens, Fucheng et al. (2014) reported that erosion rate initially increased and then decreased with increasing sand content at a fixed pressure drop; the degree of the erosion peaked at the sand content of 10%. Moreover, for slotted screens studied by Liu et al. (2009), the erosion rate initially increased as the sand particle diameter

Fig. 10 Plot of Procyk et al. (2015) for the effect of particle concentration at constant face velocity (0.73 m/s) on woven wire mesh erosion

and sand concentration increased. Then, it decreased after reaching certain values of sand particle diameter and sand concentration. Similarly, Zamberi et al. (2014) found that the erosion rate linearly increased with increasing sand loading up to 1% vol–vol concentration before converging to a plateau at around 5% vol–vol concentration. Deng et al. (2019b) explained the reduction in erosion by the fact that the carrying ability of sand by fluid with a specific velocity is limited for too high sand content. Thus, the fluid cannot deliver enough energy to the sand and consequently erosion reduces. Furthermore, collision between particles reduces the energy of the moving particles. Additionally, when sand content is too large, bridging easily occurs which can reduce the erosion effect (Zamberi et al. 2014). It has been indicated that at high concentrations, when particles rebound from the wall, they strike particles that move towards the wall, which slows them down. This phenomenon is referred to as ‘shielding’ or ‘cushioning’ (Deng et al. 2005).

Carrier fluid type and properties

Another essential consideration for erosion testing is the carrying fluid type. For sand screens, several experimental studies have been conducted using water as the carrier fluid, such as McKeon et al. (2017), Charles and Fipke (2017), Procyk et al. (2015), Zamberi et al. (2014), and Gillespie et al. (2009). Conversely, other studies such as Kanesan et al. (2019), Kumar et al. (2018), and Zamberi et al. (2014) used gas or air. However, few experimental studies used viscous fluids to study erosion of sand screen, such as Deng et al. (2019a) and Liu et al. (2009), in which oil was used, and Gillespie et al. (2009), in which glycol was used. For computational fluid dynamics (CFD) studies, Zhang et al. (2020), Zamberi et al. (2014), and Greene and Moen (2012) used gas/air. Others, including Charles and Fipke (2017) and Procyk et al. (2015), used water and Fucheng et al. (2014) used oil for their simulations. Procyk et al. (2015) highlighted the importance of considering the fluid type, where they stated that one factor not addressed in the application of

their erosion model to field data was the difference between erosion in a solid/gas and that in a solid/liquid stream.

Although one may suppose that erosion in a gas stream is much higher than that in a solid/liquid stream because of the lack of a protective viscous fluid layer coating the surface, which is found in a solid/liquid stream, other factors can affect the relative erosion rates between the two types of carrier fluids (Procyk et al. 1998). For instance, Cameron and Jones (2007) reported some data showing significantly higher erosion rates in a solid/liquid stream than in a solid/gas stream under similar flow conditions. This was due to the poor efficiency of the gas to accelerate particles from the screen entrance through the woven wire matrix relative to the liquid test. Similarly, Gillespie et al. (2009) tested the erosion rates between sand/water and sand/glycol and found higher erosion rates with the more viscous glycol, reportedly for the same reason. Admittedly, this is strictly a function of the carrying capacity of the fluid and not an intrinsic property of the erosion rate between solid/gas and solid/liquid systems. However, it may reflect the actual well conditions. One might expect similar limitations in gas streams relative to the liquid transport of sand in short open perforation tunnels or transport of fines through the sand or gravel matrix (Gillespie et al. 2009). The experiments conducted by Gillespie et al. (2009) did not show any plugging for the water test runs. Some plugging occurred during the glycol tests, where the pressure increased by approximately 33% from its initial value. This is possibly because of the size ratio of the grit used for the MMS 135 mesh. From the above studies, it is clear that more experimental studies on sand screen erosion, considering the effect of fluids density and viscosity, are needed for better understanding of erosion phenomena and mechanisms.

Comparison of experimental designs of screen erosion tests

Experimental studies on sand screen erosion are summarized and compared in Table 3. Looking at Table 3, from the design of experiment (DOE) perspective, most of the experiments took the approach of one variable at a time (OVAT) with which interaction effects cannot be obtained. Designing an experiment means choosing the optimum experiment design to be applied simultaneously for changing all the analysed factors (Aziz et al. 2008). DOE methods should be used to obtain more precise interaction effects and correlations. Moreover, regarding the fluids used during experiments, very few studies were conducted using viscous fluids which can provide more realistic behaviour, especially for oil wells. As shown in previous sections, fluid type can have remarkable effects on erosion, as it affects impact velocity and the carrying capacity for particles. Hence, more

Table 3 Experimental studies comparison

Author (year)	Screen type	Tested screen geometry	Carrier fluid	Fluid velocity	Solid particle/sand type	PSD	Sand concentration
Kumar et al. (2018)	wire-wrapped screen	Cylindrical vertical	Air	Variable	Three types of SiO ₂ sand	Variable	Variable
McKeon et al. (2017)	wire-wrapped screen	Circular coupon	Water	Constant	Silicon carbide particles	Constant	Constant
Charles and Fipke (2017)	wire-wrapped screen	Cylindrical horizontal	Water	Constant	Silica sand	Variable	Constant
Gillespie et al. (2009)	wire-wrapped screen	Flat screen disc	Water and glycol ($\mu = 50\text{cp}$)	Variable	Silicon carbide grit	Variable	Constant
Hamid and Ali (1997)	wire-wrapped screen	Cylindrical horizontal	Water	Variable	(Sands of 200 and 100 U.S. mesh were used as fines)	Variable	Variable
Deng et al. (2019a)	Monolayer metal wire mesh	Circular sheet	Oil $\mu = 20\text{ mPa}\cdot\text{s}$	Variable	Sand	Constant	Constant
				Constant	Sand	Variable	Constant
				Constant	Sand	Constant	Variable
Kanesan et al. (2019)	Wire mesh	Circular Coupons	Air	Variable	Silicon oxide (68%) and Oxygen (32%)	Variable	Constant
Kumar et al. (2018)	Premium metal mesh	Cylindrical	Air	Variable	Three types of SiO ₂ sand	Variable	Variable
Procyk et al. (2015)	Woven wire mesh Gravel/frac packing	Stacked coupons	Water	Variable	Silicon carbide	Constant	Constant
Zamberi et al. (2014)	Wire mesh	Cylinder-In-Pipe Horizontal	Air and water	Variable	Sand	Coarse and fine PSD	Variable

experimental studies using different fluid types are needed. Also, the comparison shown in Table 3 with respect to the geometry of the tested screen sample reveals that most experiments have been conducted on circular coupons, which cannot fully simulate the condition of the wellbore.

Conclusions

In this paper, the key factors influencing the erosion of sand screens were described based on in-depth analysis and evaluation of the previous experimental-based results. Table 4 provides a summary of observations and findings of previous studies on parameters affecting sand screen erosion and the associated challenges and limitations. The following are the main conclusion and findings.

- In general, the erosion rate increases with the carrier fluid velocity. A relatively small increase in fluid velocity can have a huge impact on the specific erosion.
- At low velocities, the relationship between erosion and velocity can be linear at constant particle size and concentration. However, a nonlinear power-law relation-

ship was observed when the particle concentration was changed with increasing velocity.

- The relationship between erosion rate and particle size is generally nonlinear.
- Particle velocity can remarkably differ from the carrier fluid velocity, particularly if liquid is used as the carrier fluid.
- Most of the experimental studies on sand screens found that, as the sand concentration increases, the erosion of sand screens initially increases and then decreases after reaching a certain peak value.
- Plugging is considered a phenomenon that provokes erosion. However, studies regarding the plugging-induced erosion of sand screens are very limited. Therefore, the mechanism of erosion in this case needs to be understood and examined.
- Carrier fluid type is found to have a significant effect on particles velocity and subsequently on erosion. Some studies found that significantly high erosion rates can be obtained in a solid/liquid flow than those in a solid/gas flow under similar flow conditions.
- Most of the experimental studies have been conducted using air or water as carrier fluids. Very few studies on sand screens were conducted using more viscous fluids. Therefore, more studies are needed to examine sand

Table 4 Observations and findings of previous studies on parameters affecting sand screen erosion and the associated challenges and limitations

Factor affecting erosion	Observations and findings	Experimental challenges and limitation
Impact velocity	<p>Erosion rate increases with velocity</p> <p>An exponential and power-law relationship between erosion and velocity were observed</p> <p>The fluid flow velocity can decrease as the sand content increases</p> <p>Some studies found that, below a critical velocity, no measurable erosion was observed, but above the critical velocity, the erosion increased almost with the velocity</p>	<p>For experiments where gas is used as a carrier fluid, some studies found that, gas velocity is not the same as the particle impact velocity because of a slip velocity between sand particles and gas</p> <p>The fluid/particle velocity should be corrected with respect to the area open to flow</p>
Impact angle	<p>For ductile materials, maximum erosion rates occur at lower impact angles</p> <p>Conversely, the highest erosion for brittle material occurs at angles near the normal impact angle (90°) since the main cause of erosion of brittle materials is cracking</p>	<p>Fluid type should be taken into consideration, because, in slurry flows, sand particles tend to follow the fluid streamlines. Hence, particles impact the surface at various ranges of impact angles and speeds</p> <p>Test geometry and orientation is a very essential factor that affects the impact angle of solid particles during experiments</p>
Particle size distribution	<p>As the particle size increases, erosion increases and then decreases after a peak value is reached</p> <p>Some studies found that, the erosion rate shows an exponential relation with particle size</p> <p>Poorly sorted sand with more fines can result in more erosion damage than well-sorted uniform sand</p> <p>In relatively high fine contents system, fine particles and cause screen plugging at the areas of screen influx, which will subsequently cause hot spots for erosion</p>	<p>Some experiments had been conducted under sieved or constant particle size for test operational considerations and prevention of screen plugging</p> <p>The plugging-induced erosion is one of the areas that requires further studies and simulations</p>
Particles concentration	<p>Studies found that, the erosion rate increases as sand concentration increases</p> <p>It has been observed that, erosion decreased after reaching certain values of sand concentration</p>	<p>More experimental data are needed to clearly find the mathematical relationship between erosion and particle concentration under various conditions</p>
Carrier fluid type	<p>Some experimental results showed significantly higher erosion rates in a solid/liquid stream than in a solid/gas stream under similar flow conditions</p>	<p>Experimental studies on sand screen erosion, considering the effect of fluid types, density and viscosity are limited</p>

Table 5 Future studies outlook

Issue/Challenge/Shortcomings	Proposed pathway/methodology
Particle velocity can remarkably differ from the carrier fluid velocity, particularly if liquid was the carrier fluid	Conduct numerical simulation where four-way coupling is considered Conduct erosion test under gas flow and compare the results with liquid flow tests of different viscosities
The erosion test setup and orientation play a significant role in simulating the erosion behaviour of materials under different flow conditions. Most studies are on linear flow and on circular coupon samples	Figure 11 shows the proposed test section for radial flow orientation measurements Figure 12 shows the proposed experimental setup for plugging-induced erosion test. Velocity measurements upstream and downstream of the screen sample along with the pressure drop measurement can be used to quantify plugging effects under specific conditions
Flow conditions around stand-alone sand screens should be considered when modelling or simulating erosion, such as flow direction, annulus condition and plugging tendency	Erosion should be measured under each condition of partial plugging for specific PSD Correlation including a factor which quantifies plugging should be obtained
Erosion magnitude is a function of impact angle, which itself depends on the carrying fluid, flow direction and geometry	Figure 13 shows the proposed setup that can consider the effects of impact angle and flow direction Erosion investigation with this setup should provide comparisons of erosion magnitude and pattern depending on the surface curvature and fluid flow properties
Some studies are conducted under constant or sieved PSD to prevent plugging, although plugging is expected under normal field conditions and PSD could be changing with time as production progresses	Figure 14 shows a representation of a sand screen under retention condition The effect of fine particles can be studied under partial plugging and sand retention conditions
Some of the experiments were of the one-variable at a time (OVAT) type with which interaction effects cannot be obtained	DOE methods can be used to obtain more precise interaction effects and correlations, using full or fractional factorial design Analytical tools such as interactions plots, cube plots response surface plots and regression models DOE analytical tools can be used to identify the contribution and/or domination of certain parameters on erosion magnitude, under various condition
There is a challenge regarding erosion measurements from experimental investigation, as far as scaling of lab tests to full-scale application under various geometries and flow conditions	For erosion quantification, to compare various geometries and flow conditions, it is useful to express erosion in terms of specific erosion Specific erosion is the total mass loss of a material divided by the total mass of solid particles that have impacted the material in a given period of time
The review and comparison of experimental studies, with respect to the geometry of the tested screen sample, revealed that, most experiments have been conducted on circular coupons, which cannot fully simulate the condition of the wellbore	To conduct erosion testing on a full geometry of a sand screen If tests cannot be run on full screen geometry, representative samples can be used, such as the sample shown in Fig. 11 Computational fluid dynamics modelling can be used for preliminary simulations and experimental conditions setup
Some studies revealed that, if the fluid velocity is very high during the experiment, the screen will be eroded very quickly, and if the sand content is too high, sand will accumulate on the slot. Hence, this could result in experimental data that contradict the field data	Simulated conditions should represent field data and near wellbore conditions should be analysed. Flow regimes and expected velocity ranges should be estimated accurately such that experimental results reflect what happens under real flow scenarios If sand particles are expected to be increasing with time, prediction models can be incorporated during experimental design

screen erosion under various conditions of fluid viscosity and density.

- The geometry of screen samples of most studies was circular coupons. There is a need to have experimental setups which can fully simulate the conditions of the wellbore with respect to flow geometry, sample shape, and orientation.

Outlook

In this section, the outlook and proposed pathways for future research on sand screen erosion are presented. Table 5 shows the issues and challenges associated with the previous studies along with the proposed pathway to overcome or investigate those issues and address the challenges. The issues are related to the limitation of the previous studies as far

Fig. 11 Proposed experimental orientation for radial flow orientation

Fig. 12 Proposed experimental setup for plugging-induced erosion test

Fig. 13 Proposed setup for impact angle and flow direction effect quantification: (a) flat screen and (b) cylindrically curved screen

as test setup and flow direction are concerned. Moreover, some of the limitations are associated with particle–particle interaction and particle–fluid interaction considerations. The presented proposals will pave the way for future studies and enhance the experimental outputs of sand screen erosion.

Fig. 14 Sand screen under sand retention condition

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Declarations

Conflict of interest The authors declare no conflict of interest.

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