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# A Novel Approach for Using Silica Nanoparticles in a Proppant Pack to Fixate Coal Fines

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## Abstract

Hydraulic fracturing operations in coal seam gas (CSG) reservoirs are highly prone to release coal fines. Coal fines inevitably cause mechanical pump failure and permeability damage as a result of their hydrophobicity, aggregation in the system, and pore-throat blockage. Thus, one approach to affix these coal fines at their source, and to retard generation, is to introduce a nanoparticle-treated-proppant pack. Thus, this research explores coal fines retention (known as adsorption) in a proppant pack using nanoparticles. In the study, the electrolytic environment, pH, flow rate, temperature, and pressure were kept constant, while the variables were concentration of silica nanoparticles (0 – 0.1 wt%) and coal fines concentration (0.1 – 1 wt%). The objective was to identify silica nano-formulations that fixate coal fine dispersions effectively. Subsequently, the coal suspensions flowed through a glass bead proppant pack treated with and without nanoparticles, and then analyzed via a particle counter. The quantitative results from particle counter analysis showed that the proppant pack with nanoparticle treatment strongly affects the fixation ability of coal fines. The proppant pack without nanoparticle treatment showed up to 30% adsorption and flowed through the proppant untreated, whilst proppant pack treated with nanoparticles showed up to 74% adsorption; hence, more exceptional affixation ability to the coal fines. Further, the results indicated that the zeta potential of silica nanoparticles at higher salinity becomes unstable, i.e., ~ -20 mV; this low value helps the proppant pack treated with nanoparticles to attach coal fines to it. The ability of nanoparticles to adsorb coal fines is due to its highly active surface, and high specific surface area.

## Keywords

Coal fines, nanoparticles, nanofluid, fines fixation, CBM, Proppant pack

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## 1. Introduction

The application of nanoparticles has proven to be beneficial in the upstream oil and gas industry (Yang *et al.* 2015). Several applications like water flood displacement (Yuan and Moghanloo 2018; Bahraminejad *et al.* 2019; Najimi *et al.* 2019), fines fixation (Huang *et al.* 2010b; Assef *et al.* 2014; Yuan 2017; Zheng *et al.* 2018), and enhanced oil recovery (Yousefvand and Jafari 2015; Bera and Belhaj 2016; Yuan and Wood 2018; Asl *et al.* 2020) have been studied and experimented upon in this capacity. The use of nanoparticles to control fines release and fix them at or near the source of their origin has been studied comprehensively in both sandstones (Kia *et al.* 1987; Mohan and Fogler 1997; Rozo *et al.* 2007; Zeinjahromi *et al.* 2012; Bin *et al.* 2016; Hasannejada *et al.* 2017) and carbonates (Qajar *et al.* 2013; Al-Anssari *et al.* 2016; Al-Anssari *et al.* 2017b; Al-Anssari *et al.* 2018). The behavior of Coal Bed Methane (CBM) reservoir fines with nanoparticles, which are considerably different from sandstone fines, has yet to be comprehensively explored.

Compared to conventional reservoirs, CBM reservoirs are relatively weaker and are likely to fail in all operating stages of well development, especially while drilled in horizontal or high-angle directed trajectories (Palmer *et al.* 2005). CBM reservoirs have critical conditions to release fine. A critical salt concentration (CSC) exists in porous media (Khilar and Fogler 1984; Blume *et al.* 2005) below which fines can detach from the rock matrix. However, no presence exists of the validated agreement as to CSC in fractured media. The theoretical explanation of fines detachment / attachment has been explained using the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory and extended DLVO theory. The basic premise is that if the attaching force/torque is higher than the detaching (repulsive) force/torque, then the particle will dislodge from the bulk rock matrix/structure and vice versa if the detaching (repulsive) force/torque is higher than the attractive force/torque. (Lever and Dawe 1984; Sharma *et al.* 1992; Schembre and Kovscek 2005; Rosenbrand *et al.* 2015). The size of coal fines varies according to the production stage, i.e., the usual size of coal fines found during the water production stage is usually lower than the size of coal fines generated during the gas production stage. When salinity is decreased, mobile particles also decrease in the order of size. This means that larger particles are released when ionic strength is more, and when ionic strength is decreased the smaller particles are mobilized (Keshavarz *et al.* 2014). The grain size and concentration of coal fines differ during various production stages (Zhao *et al.* 2016). Generally, two size categories can be distinguished, as follows:

35 1. Small-sized coal fines are produced during post-completion hydraulic fracture back-flow  
36 and in the production stage.

37 2. Large-sized coal fines are produced during drilling and completion (Han *et al.* 2015).

38 Coal fines generation and migration cause a reduction in conductivity and fracture length,  
39 thereby damaging the dewatering process (Zou *et al.* 2014). The factors that affect the  
40 production of coal fines output are:

41 1. Engineering aspects (well type, drilling operations/technology, hydraulic fracturing,  
42 completion technology, and the CBM production system) (Zhao *et al.* 2016; Geng *et al.*  
43 2017).

44 2. Geological factors (tectonic stress, rock characteristics, structural characteristics of the  
45 coal, coal strength) (Zhao *et al.* 2016).

46

47 Bituminous coal fines have been shown to cause a 35% decline in permeability when subjected  
48 to water flow (Guo *et al.* 2016) and a 24.4% decline in conductivity when subjected to only  
49 2% of coal fines flow into the proppant pack (Zou *et al.* 2014). Thus, coal fines can block the  
50 proppant pack and cause a decline in fracture conductivity (Bai *et al.* 2017), resulting in  
51 reduced production and failure of production equipment (Marcinew and Hinkel 1990;  
52 Badalyan *et al.* 2016). Several authors have studied coal fines suspension thus far, but have  
53 largely performed experiments in DI or distilled water (Zou *et al.* 2014), while hydraulic  
54 fracturing fluid is usually saline (nearly 0.6 M) to be geo-chemically compatible with reservoir  
55 formations fluid (Guo *et al.* 2015; Patel *et al.* 2016; Shi *et al.* 2018). The zeta-potential of coal  
56 suspension in DI water has been reported as -43.34 mV for bituminous (Shi *et al.* 2018) and  
57 anthracite as -20.5 mV (Zou *et al.* 2014); however, pH has not been mentioned as a crucial  
58 factor in determining the dispersion stability via zeta-potential measurements and has not been  
59 studied accordingly.

60

61 Fixating coal fines at their source of origin may be done by:

62 a) using nanoparticles and modified nanoparticles that alter the surface chemistry of fines  
63 by interacting with nanoparticles (Huang *et al.* 2010a),

64 b) employing micro-proppants before introducing larger proppants (also known as graded  
65 proppant injection) so that the fine particles are inhibited from moving into the proppant

66 pack at or near its place of origin (Kumar *et al.* 2012; Keshavarz *et al.* 2014; Keshavarz  
67 *et al.* 2015; Keshavarz *et al.* 2016),

68 c) adding chemicals to the fracturing fluid for agglomerating fragments of coal fines and  
69 fixing them at the source (Shi *et al.* 2018). Consequently, dispersing coal fines can be  
70 completed via two modes: physical and chemical.

71 i. Physically, researchers have developed models for straining particles in the pore  
72 throat, where the critical value of consensus among them is of one to six ratio, also  
73 known as a one-sixth rule. This rule notes that if the reservoirs formation fines  
74 diameter (d) is six times less than its gravel pack diameter (D) i.e.  $\frac{d}{D} < \frac{1}{6}$ , the fines  
75 will not strain (Elena Rodríguez 2007; Zou *et al.* 2014).

76 ii. Polymeric surfactant-based chemicals injected along with fracturing fluid to  
77 disperse and move up to the surface along with well fluids (Magill *et al.* 2010);  
78 (Pan *et al.* 2015).

79

80 Thus, fines migration is one of the most crucial phenomena for formation damage in CBM,  
81 where this challenge has not been addressed comprehensively. Limited studies are available to  
82 suggest that coal fines generation could be controlled at or near the source using metal oxides  
83 nanoparticles (Huang *et al.* 2010a; Patel *et al.* 2016). This paper will provide further insights  
84 into coal fines behavior when treated with silica nanoparticles in a proppant pack. The results  
85 show that coal fines can be adsorbed effectively using silica nanoparticles (NPs). An effective  
86 concentration of 0.1 wt% of silica NPs is recommended for achieving better adsorption of fines.

87

## 88 **2. Methods and Materials**

### 89 *2.1. Materials*

90 Coal lumps from coal mines in Morgantown, West Virginia, USA, were retrieved with a  
91 vitrinite reflectance of 0.91, indicative of highly volatile bituminous coal (Moore 2012).  
92 Furthermore, the composition of macerals and minerals was 97.4% and 2.6%, respectively. The  
93 properties of the coal sample are displayed in Table 1. The coal lump was crushed into smaller  
94 sizes by mortar and pestle method, where the coal fines used in this study were sieved using an  
95 electric sieve shaker. Subsequently, the coal fines sieved in 0.038 mm – 0.020 mm were used  
96 for the series of the experiment of adsorption and coal fines fixation in the proppant pack  
97 column. The coal fines size range studied in this work (0.038 mm – 0.020 mm) is consistent

98 with previously reported studies (Huang *et al.* 2010a; Bai *et al.* 2015; Zhao *et al.* 2016; Bai *et*  
99 *al.* 2017).

100

101 The glass bead proppant was kindly provided by Potters beads of Metal Finishing Glass  
102 Beads Potters, with a nominal diameter (80%) Ballotini ® Metal Finishing Beads of Potter  
103 Designation B, US Sieve 30-40 (600-475 microns), and minimum roundness of 65%, where  
104 the composition of glass beads can be seen in Table 2. Using the electrical sieve shaker,  
105 proppants were sieved to US sieve size of 35 (~475 microns) that were used in the adsorption  
106 proppant pack experiments.

107

108 The silica nanoparticles are insoluble, hydrophilic, and non-polar in water, where those  
109 used in this study were procured from Sigma-Aldrich. The properties of the silica nanoparticles  
110 are presented in Table 3. An electrolyte of 0.6 M NaCl (as compared to standard saline) was  
111 used in the adsorption experiments. A constant pH of  $9.0 \pm 0.2$  was set in all of the experiments  
112 as similar to coalbed methane reservoirs. Various concentrations of silica nanoparticles were  
113 used to formulate nanofluids. DI-water (Ultrapure Type 1 Water) was used as a base fluid for  
114 the nanofluid and to formulate 0.01 M and 0.6 M brine after mixing with NaCl (58.44 g/mol,  
115 purity  $\geq 99.5$  mol%, from Rowe Scientific).

116

## 117 2.2. Methodology

118 Various SiO<sub>2</sub> NPs concentrations (0.01 – 0.1 wt%), based in 0.01 M and 0.6 M brine-  
119 based solutions, were investigated in various coal concentration (0.1-1 wt%) to examine their  
120 stability, adhesion to the glass beads proppant, and coal fines adsorption efficiency. The  
121 formulation of nanofluids was carried out with two constituents, the dispersed phase and the  
122 dispersion medium. The dispersed phase was nano-sized silicon dioxide (SiO<sub>2</sub>) - also known  
123 as SNPs or Silica NPs, with weight percentages ranging from 0.01 to 0.10, while the dispersion  
124 medium was DI water, 0.01 M and 0.6 M NaCl. The dispersion stability was investigated using  
125 Malvern Z3600 Nano zeta sizer. The nanofluids were formulated by sonicating nanoparticles  
126 in the base fluid (Mahdi Jafari *et al.* 2006) using an ultrasonic processor (VCX 750, a 750-watt  
127 ultrasonic processor, frequency - 20 kHz from Sonics & Materials, Inc.). Whilst the time and  
128 power of the sonication process depends mainly on a load of dispersed nanoparticles (Shen and  
129 Resasco 2009), in this work all the formulated dispersions were sonicated with the same  
130 sonication time, energy, amplitude and power of 300 seconds, 4 MJ, 30%, and 240 V  
131 respectively to assure a duplicated conditions for all formulations. The prepared nanofluids

132 were visually observed to assess any significant instability in the behavior of the nanoparticles  
133 during the required soaking period. All experiments were carried out under ambient conditions  
134 of pressure = 101.3 kPa and temperature of  $295.15 \pm 3$  K.

135

136 The process of adsorption of sandstone fines using nanoparticles affixed on glass beads  
137 has also been studied by Huang et al. (2008) and Ahmadi et al. (2013) in addition to other  
138 researchers (Huang *et al.* 2008b, 2008a; Belcher *et al.* 2010; Huang *et al.* 2010b; Ahmadi *et al.*  
139 2013b, 2013a; Habibi *et al.* 2013; Habibi *et al.* 2014). However, SNPs coating onto the  
140 proppant pack quantitatively has only been discussed by a few researchers such as Abhishek  
141 and Hamouda (Abhishek and Hamouda 2017). The only reported patent of using nanoparticles  
142 for affixing coal fines highlights the use of MgO to affix coal fines (Huang *et al.* 2010a). The  
143 selection of the proppant is influenced by the mechanical properties of the formation rock and  
144 the properties of the proppant itself. The parameters that impacted the selection of the proppant  
145 include crush resistance and size of the proppant amongst others. Hollow glass spheres have  
146 been reported to have the least specific gravity of 0.8 to 1.4 in all the lightweight proppants  
147 (Parker *et al.* 2012; Liang *et al.* 2016).

148

149 The method of affixing nanoparticles onto the surface of proppants is critical to the  
150 experiments; thus, in this research, we have soaked the NPs for 24 hours and calculated the  
151 nanoparticle coating efficiency via turbidity results. Note that SDBS (an anionic surfactant) is  
152 used in all experiments to flow through the slurry with minimal adsorption. The adsorption  
153 efficiency is defined in Eq. 1 (Habibi *et al.* 2014). The results of influent and effluent slurry  
154 were obtained using the particle counter sizer.

$$155 \quad \text{Adsorption efficiency (\%)} = 100 - \left[ \frac{C_{\text{eff}}}{C_{\text{in}}} \times 100 \right] \quad \text{Eq. 1}$$

156 Where,

157  $C_{\text{eff}}$ : Concentration of coal fines in the effluent slurry, gm/cc

158  $C_{\text{in}}$ : Concentration of coal fines in the influent slurry, gm/cc

159

160 A glass column was used in all of the experiments of adsorption, in which flow took place  
161 merely because of gravitational force, where a schematic of the procedure adopted in the  
162 column can be seen in Fig. 1 below.

163

164 2.3. *Experimental set-up workflow*

165 The laboratory study model and equipment will be adapted from Habibi et al. and  
166 Ahmadi al. and used to see the effect of silica nanoparticles on coal fines adsorption (Ahmadi  
167 *et al.* 2013b, 2013a; Habibi *et al.* 2013; Arab *et al.* 2014; Habibi *et al.* 2014). In this study, bare  
168 silica nanoparticles, as well as treated silica nanoparticles with Sodium Dodecyl Benzene  
169 Sulfonate (SDBS), were analyzed with a Malvern Nano Zeta Sizer to determine their stability.  
170 Following this, a turbidity calibration curve for silica NPs was made using a HACH 2000  
171 Turbidimeter. The main experiment was the proppant pack tests conducted in the glass column  
172 at ambient conditions in which coal slurry flowed into a proppant treated with SNPs. This was  
173 compared with proppant without any SNP treatment. The results of the coal slurry were  
174 obtained using a particle counter analyzer. The corresponding experimental workflow is shown  
175 in Figure 2.

176

### 177 **3. Results and Discussion**

#### 178 *3.1. Silica Nanoparticles dispersion using SDBS*

179 In order to modify the dispersion stability and surface chemistry of SNPs, an anionic surfactant  
180 SDBS was used. In the three dispersion mediums (DI water, 0.01 M NaCl, and 0.6 M NaCl)  
181 tested, SDBS reduced the zeta-potential and effectively enhanced the dispersion stability, as  
182 shown in Figure 3. Note that the dispersion stability is more effective in DI water and low  
183 salinity (0.01 M NaCl) rather than in the high salinity (0.6 M NaCl) suspension.

184

185 The zeta-potential measurements of bare SNPs in both ionic strengths are consistent with Al-  
186 Anssari et al. (2017) (Al-Anssari *et al.* 2017a). With increases in ionic strength, the absolute  
187 zeta-potential value decreases, resulting in reduced dispersion stability. However, the DI water  
188 and low ionic strength (0.01 M NaCl brine) provide better stability enhancement when SNPs  
189 are treated with SDBS.

190

#### 191 *3.2. Effect of Nanoparticles adhesion onto proppant pack*

192 In order to examine the coating of nanoparticles via the soaking method, we first calibrated  
193 SNPs in DI water. The SNPs turbidity increases with an increase in SNP loading, as can be  
194 seen in Figure 4. Note that the turbidimeter has a limitation of 1000 NTUs. When on the x-  
195 axis, SNP loading is increased while on the y-axis, the turbidity value in NTU increased with  
196 the loading resulting in a slope value of 3390.5.

197



198 It was observed that higher salinity has lower zeta-potential, which leads to higher retention  
199 efficiency of SNPs by soaking method, as seen in Figure 5. The results show that SNPs based  
200 in DI water yielded retention efficiency of 61-67%, while 0.01 M NaCl (as comparable to  
201 potable water) yielded 60-72% retention efficiency, and 0.6 M NaCl (as comparable to  
202 seawater) yielded 81-85% retention of SNPs onto the glass bead proppant pack. This  
203 retention is due to the zeta-potential values, as obtained in Section 3.1, which can also  
204 be seen in Figure 3. Thus, aggregation of nanoparticles in 0.6 M NaCl ionic strength  
205 due to its low zeta-potential, aids it in retaining SNPs in the proppant pack.

206

207 Thus, in further experiments after observing better retention of 0.6 M NaCl cases in two coal  
208 concentrations (0.01 wt% and 0.1 wt%), we conducted the rest of the experiments of adsorption  
209 in 0.6 M NaCl salinity. This is consistent with the DLVO theory, which defines principles  
210 based on which the particles (in our case SNPs) aggregation take place at higher salinities.

211

### 212 3.3. Effect of Chemically modified Nanoparticles on coal fines fixation

213 Chemically modified nanoparticles (in this case, silica nanoparticles treated with SDBS) were  
214 injected into the glass-column, followed by the introduction of the glass-bead proppant pack.  
215 The results showed that 0.1 wt% of SNPs yielded maximum adsorption of all tested coal fines  
216 (0.1, 0.5, and 1 wt%), as can be seen in Figure 6. Note that there is a difference in adsorption  
217 of coal fines with weight percentages (even when passing through an untreated proppant pack),  
218 as a higher concentration of slurry yields lower dispersion stability, leading to clogging in the  
219 proppant pack (Al-Anssari *et al.* 2017a).

220

221 The base case has been optimized in our previous work (Awan *et al.* 2019), giving a  $C_{eff}/C_o$  of  
222 approximately 83%, meaning the adsorption of coal fines is 17% (using 0.1 wt% coal fines  
223 treated with 0.001 wt% SDBS). The rest of the coal slurries also have 0.001 wt% SDBS, but  
224 their coal fines are of higher weight fraction. It can also be observed that untreated proppant  
225 packs in various coal concentrations result in an increasing trend to rising coal concentration,  
226 i.e., 17% adsorption for 0.1 wt% coal fines, 27% adsorption for 0.5 wt% coal fines, and 30%  
227 adsorption for 1.0 wt% coal fines. This occurs due to the lower stability of the coal slurry as a  
228 result of the increase in weight (Al-Anssari *et al.* 2017a), which ultimately causes the straining  
229 of coal fines due to their aggregation. Additionally, not all of the coal fines retention in the  
230 proppant pack is due to the interaction of attractive forces of nanoparticles with coal fines, there

231 is also an aggregation of coal fines and straining in the proppant pack as has been demonstrated  
232 by Zou et al. (2014) (Zou *et al.* 2014) which can be seen in Fig. 6.

233

234 With increasing the SNP loading in the proppant pack, its retention efficiency also increases.  
235 Thus, the nanoparticle treated glass beads can retard the mobilization of coal fines through the  
236 proppant pack and affix them near the source of their generation; thereby, reducing the damage  
237 to the pumps and minimizing the possibility of filling of the wellbore.

238

#### 239 **4. Conclusion**

240 The above sets of experiments conclude that higher salinity yields higher coating efficiency of  
241 the proppant pack via nanoparticles due to their aggregation behavior (zeta-potential values of  
242 greater than -20 mV). SDBS enhances the dispersion stability of silica nanoparticles in various  
243 salinities tested up to 0.6 M NaCl. An optimum concentration of 0.1 wt% SNPs yielded  
244 maximum adsorption of coal fines in the proppant pack at higher ionic strength (0.6 M NaCl  
245 brine).

246

247 Further studies involving a comparison of various coating methods (e.g., calcination, sintering,  
248 soaking, oil coating, etc.) for irreversibly affixing nanoparticles on the proppant pack need to  
249 be conducted, in order to optimize the coating procedure in various saline environments.  
250 Further, coal particles of different ranks need to be studied to understand the behavior of  
251 various metal oxide nanoparticles, in order to fixate these coal fines by adsorption in the  
252 proppant pack. A comprehensive study to determine the impact of adsorption on the  
253 permeability can also be studied, as its implication in the field can be detrimental to natural gas  
254 recovery.

255

#### 256 **Conflicts of Interest**

257 None.

258

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## Biographies

522 Faisal Ur Rahman Awan is a Ph.D. candidate in Petroleum Engineering  
523 at Edith Cowan University, Australia. His work focuses specifically on  
524 the coal fines fixation using nanoparticles. Mr. Awan did his Bachelor's  
525 and Master's degrees in Petroleum Engineering. He has also been serving  
526 at Dawood University of Engineering and Technology, Karachi, as an  
527 Assistant Professor in Petroleum Engineering for the last seven years. He  
528 is a member of prestigious societies such as SPE, SEG, EI, and PEC.



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531 Alireza holds a Ph.D. degree in Petroleum Engineering from the  
532 University of Adelaide, an M.Sc. degree in Reservoir Engineering from  
533 the University of Tehran (Iran), and a B.Sc. degree in Chemical-Petroleum  
534 Engineering from Petroleum University of Technology (Iran). He is  
535 presently serving as a Senior Lecturer at the School of Engineering at  
536 Edith Cowan University. Before joining ECU, Alireza was a research  
537 scientist in the CSIRO-Energy business unit, where he researched  
538 enhancing gas production from unconventional resources and CO<sub>2</sub>-  
539 sequestration. Before pursuing his Ph.D. study, he was a Petroleum  
540 Engineer in the National Iranian Oil Company (NIOC) for six years.  
541 Alireza's research interests focus on Enhanced Oil/Gas Recovery from  
542 conventional and unconventional reservoirs. He is a member of SPE.



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544 Hamed completed his Bachelor's and Master's in Petroleum Engineering.  
545 During his Master's study, he conducted numerical research on heavy oil  
546 EOR. He used two of the most professional petroleum simulators, CMG  
547 and Eclipse, in his studies. He changed his research field to Coalbed  
548 Methane in 2016 and received a scholarship for his Ph.D. studies at Edith  
549 Cowan University (ECU), Australia. For the time being, as a Ph.D. student  
550 at ECU, he is experimentally researching on Coalbed Methane productivity  
551 enhancement as his priority, and also partially on enhanced oil recovery and  
552 CO<sub>2</sub> geo-sequestration. He is a member of SPE.



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554 Sarmad Al-Anssari is currently a senior lecturer in Chemical Engineering at  
555 University of Baghdad, Iraq. He earned a bachelor's and master's degree in  
556 chemical engineering from University of Baghdad and he holds a PhD  
557 degree in chemical engineering/ Nanotechnology from Curtin University/  
558 Australia. He worked as a faculty member in the university of Baghdad for  
559 more than 10 years and recently he is adjunct lecturer at ECU Australia and  
560 external supervisor at Curtin university/ Australia. His research interest is  
561 on different applications of nanoparticles and nanofluids in different  
562 disciplines, including wettability alteration, enhanced oil recovery, and  
563 carbon capture and storage.



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Stefan Iglauer joined Edith Cowan University (ECU) in 2018 as a Professor to lead the developments in the Petroleum Engineering discipline. His research interests are in petrophysics and interfacial phenomena, mainly at pore-scale with a focus on CO<sub>2</sub> geo-sequestration and improved hydrocarbon recovery. Stefan has authored more than 250 technical publications; he holds a Ph.D. degree in material science from Oxford Brookes University (UK) and an MSc degree from the University of Paderborn (Germany). He is a member of SPE.



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Table 1: Properties of coal sample

Ash (%, db <sup>a</sup> )	Density (g/cm <sup>3</sup> )	Volatile matter (%, daf <sup>b</sup> )	C (%, daf <sup>b</sup> )	H (%, daf <sup>b</sup> )	R <sub>v</sub> , max <sup>a</sup> (%)	Vitrinite (vol% mmf <sup>b</sup> )	Inertinite (vol% mmf <sup>b</sup> )	Liptinite (vol% mmf <sup>b</sup> )
4.798	1.31	5.042	78.50	5.37	0.91	81.01	12.73	6.26

<sup>a</sup> **db**: on a dry basis; **daf**: dried ash-free; **R<sub>v</sub>, max**: maximum vitrinite reflectance; **mmf**: mineral matter free.


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Table 2: Properties of glass beads used as proppant packs

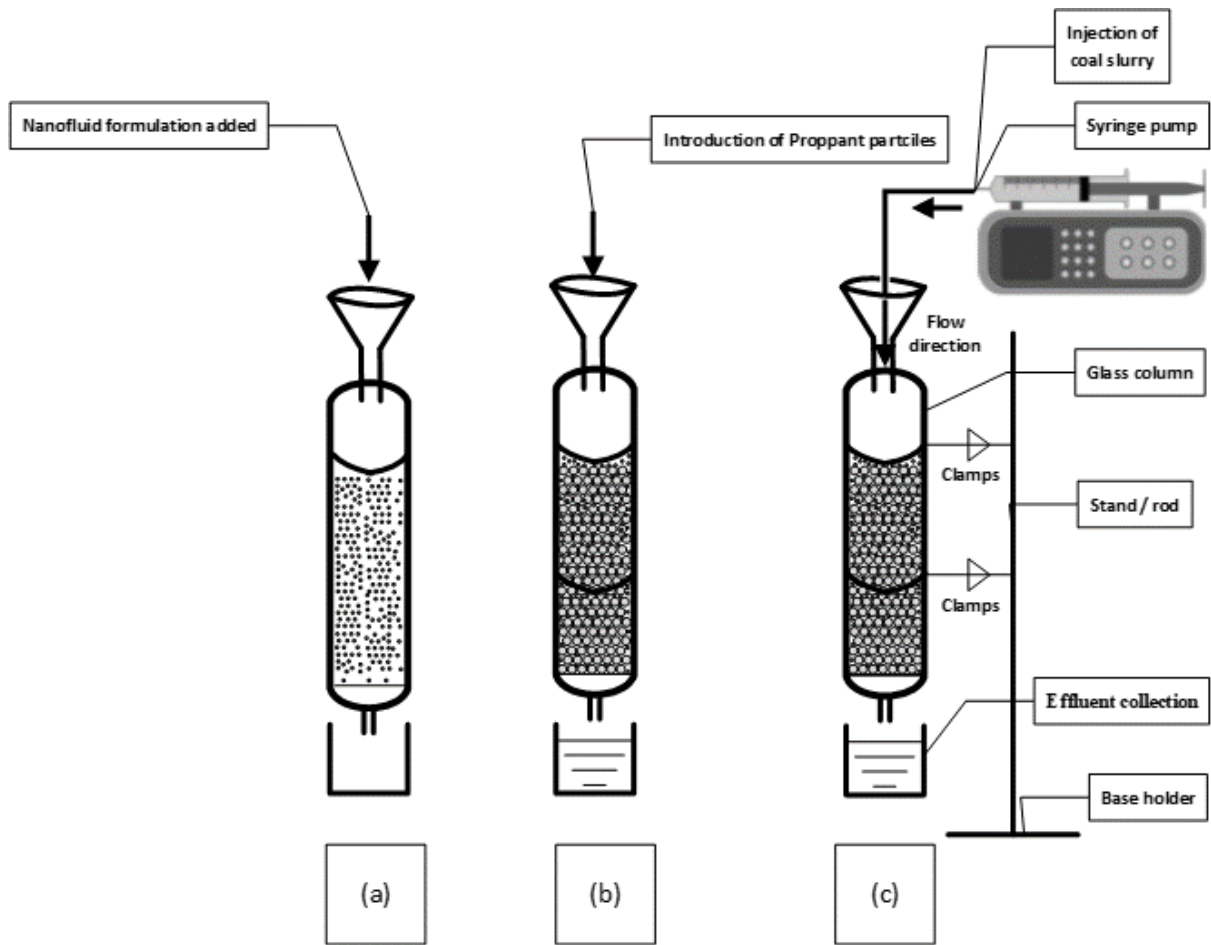
Chemical	SiO <sub>2</sub>	Na <sub>2</sub> O	CaO	MgO	Al <sub>2</sub> O <sub>3</sub>	FeO/Fe <sub>2</sub> O <sub>3</sub>	Trace
Wt %	72.5	13.6	9.7	3.4	0.4	0.2	0.2

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Table 3: Characteristics of nanoparticles

Nanoparticle	Linear Formula	Primary particle size (nm)	Chemical Structure Depiction	Specific surface area (m <sup>2</sup> /g)	Purity (%)	Density (g/cc)	Molecular mass (g/mol) @ 298.15 K	Boiling point (K)	Melting point (K)	Additional Description
Silicon dioxide	SiO <sub>2</sub>	5-15		140	≥ 99.50	2.20- 2.60	60.08	2503	1873	Porous spherical

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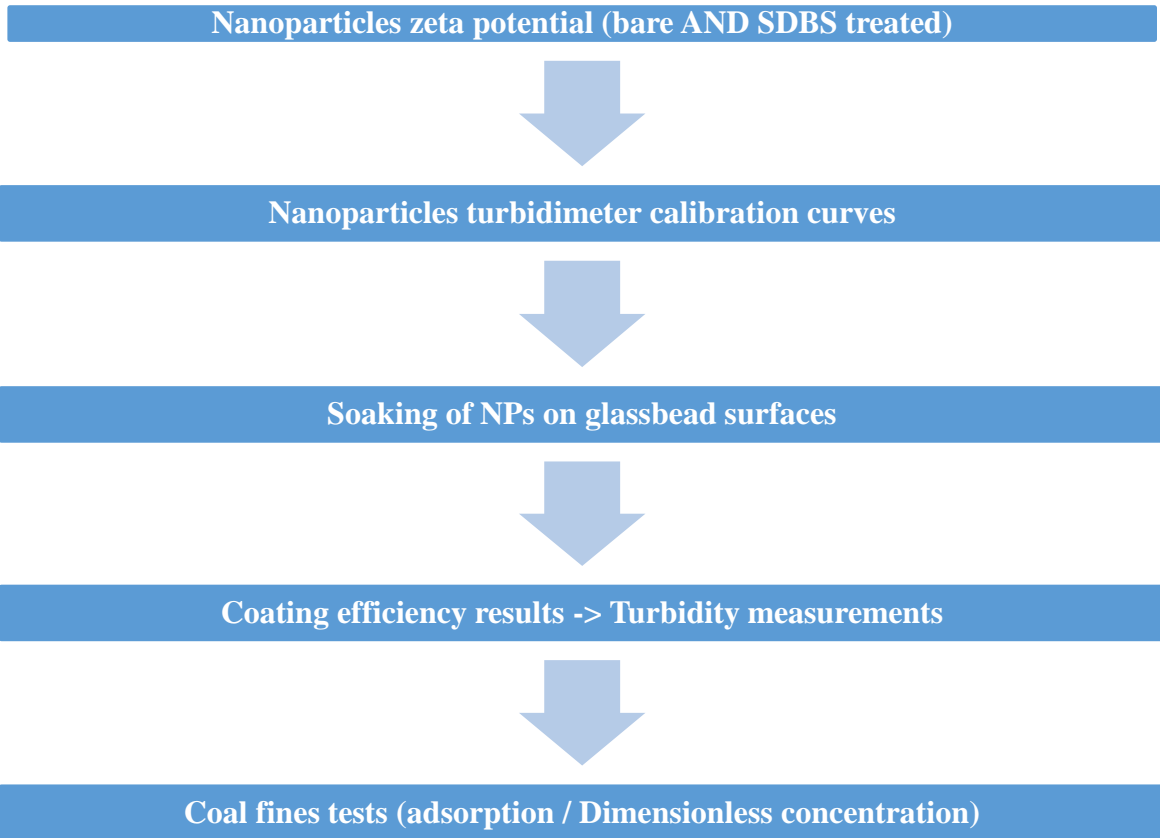
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Figure 1: Schematic of (a) Silica nano-formulation added to the glass column, (b) Introduction of proppant particles in the nano-formulation (c) Injection of coal slurry at 1 mL/min

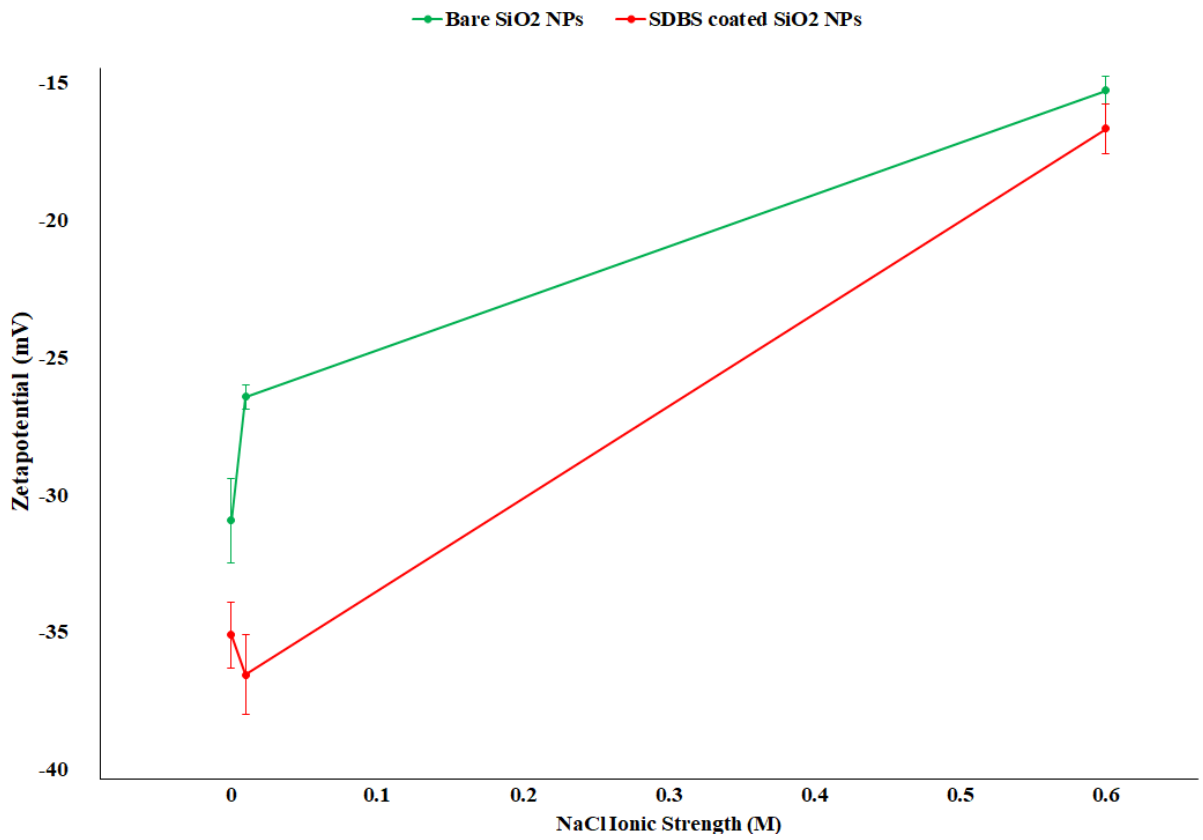


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Figure 2: Workflow of experiments for determining the effect of nanoparticles on adsorption of coal fines

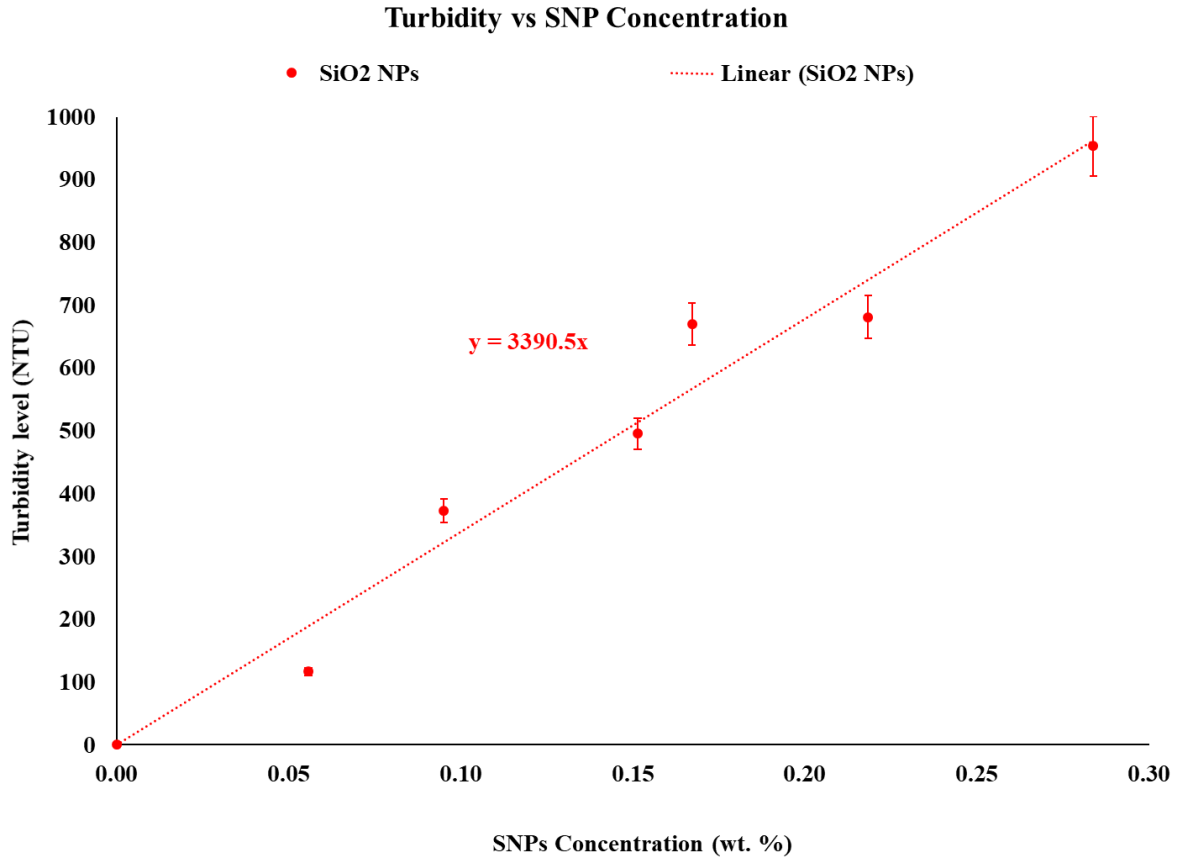


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Figure 3: Effect of SDBS in various ionic strength (0, 0.01 and 0.6 M NaCl brines) on zeta-potential for 0.1 wt% silica NPs at pH=9 and temperature=298.15 K.

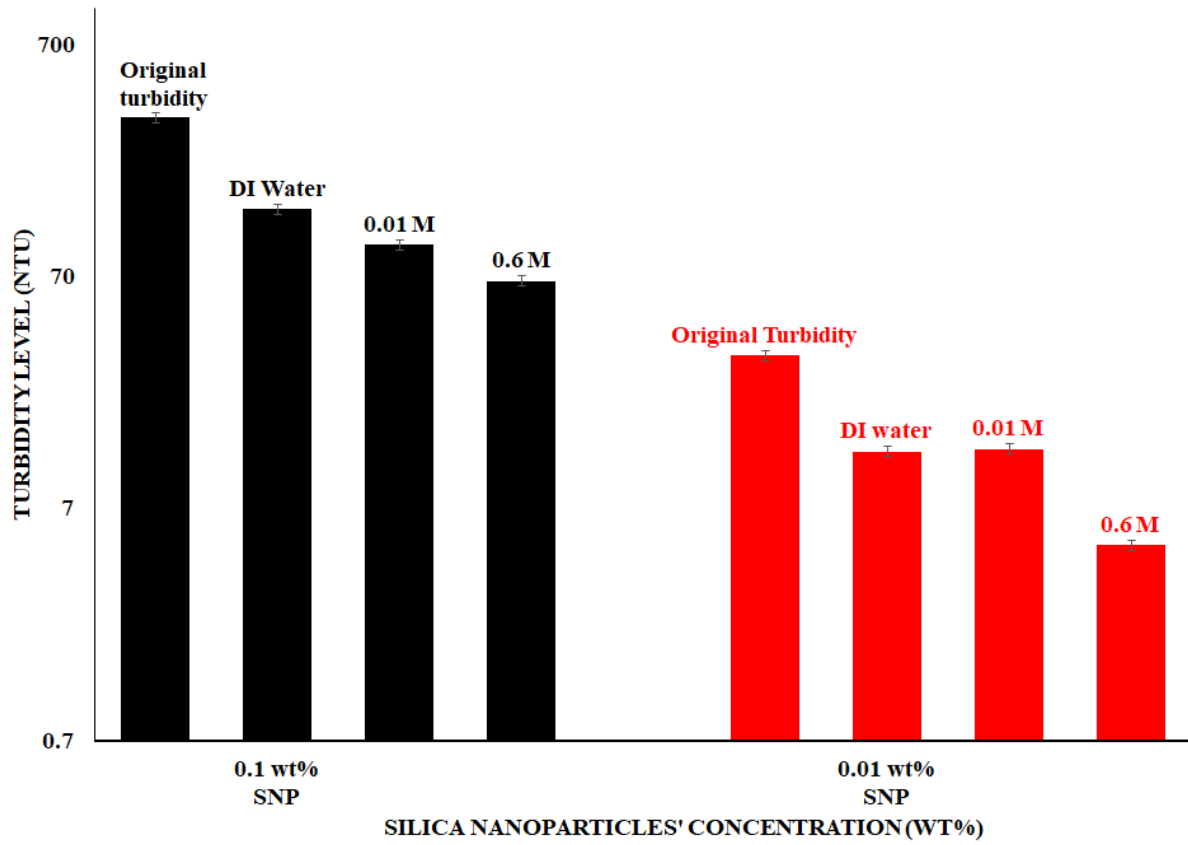


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597 Figure 4: Turbidity results of silica nanoparticles in various concentrations from 0 to 0.3 wt%

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( $R^2$  of the Linear  $\text{SiO}_2$  is 0.967)



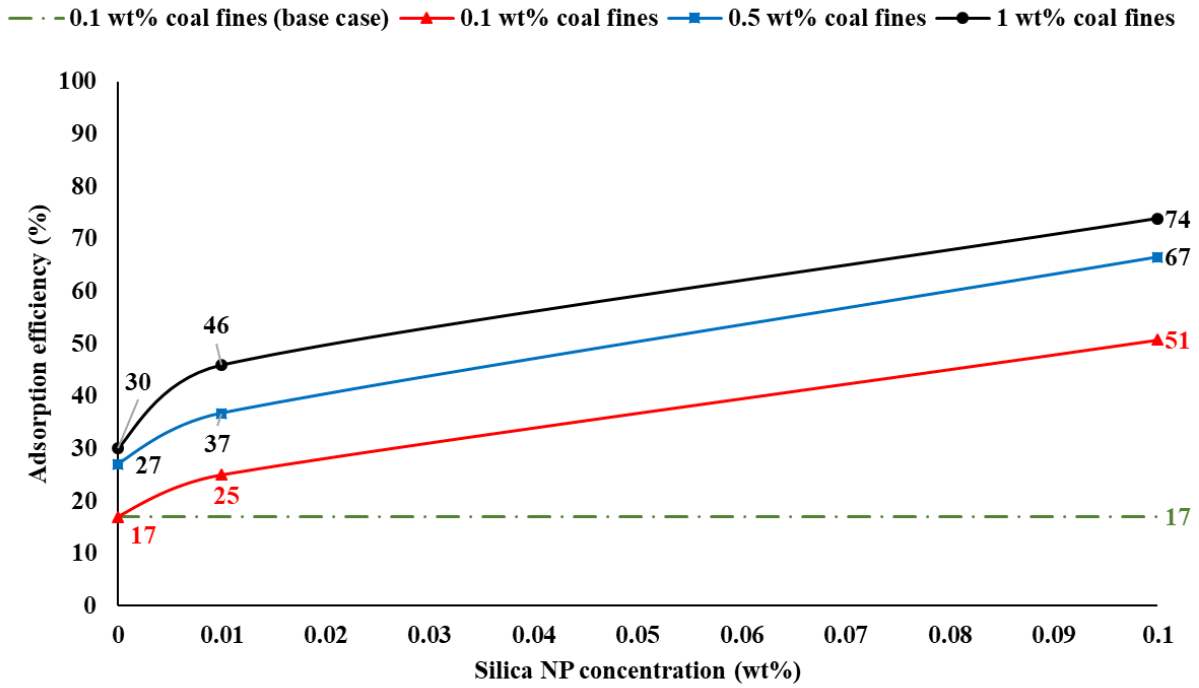
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Figure 5: Turbidity results for silica nanoparticles coating via soaking method results in various suspensions (DI water, 0.01 M, and 0.6 M NaCl brines)





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Figure 6: Results of adsorption of the various coal fines concentrations (0.1, 0.5, and 1 wt%) using no nanoparticles, 0.01 wt%, and 0.1 wt% in 0.6 M saline environment in a proppant pack. Note the base case is 0.1 wt% coal fines passed through the untreated proppant pack