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1 **Foam flow investigation in 3D printed porous media: Fingering and**
2 **gravitational effects**

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17ABSTRACT

18Flow in porous media investigations have shown foam injection have a higher
19sweep efficiency compare to gas injection. However, fingering of highly mobile gas
20into the foam bank and separation of fluids (gas and surfactant) resulted by gravity
21segregation can influence the performance of foam injection project. To the best of
22our knowledge, this phenomenon has not been investigated experimentally in the
23literature. In this study, foam injection experiments have been performed in a
24model oriented in a horizontal and perpendicular orientation with respect to gravity
25using also different flow rates. High resolution imaging tools were utilized to
26record displacement process of oil by gas/surfactant/foam. The recorded images
27enabled us to monitor gas fingering and foam flow dynamics at pore scale. The
28obtained results highlighted the adverse effect of fingering of highly mobile gas
29into the foam bank and fluids separation by gravity segregation in the performance
30of foam project.

31**KEYWORDS:** Foam flow in porous media, Gas Fingering, Gravity segregation, 3D printing
32technology, Pore-scale visualization

33INTRODUCTION

34Displacement of fluids with gas and water is a common practice in many industrial
35applications such as soil remediation, enhanced oil recovery (EOR) and CO₂ sequestration.
36Gravity segregation due to the density difference between displaced and displacing fluids
37divides the porous medium into three zones I) override zone where only the phase with the
38lower density exists, II) underride zone where only the phase with the higher density exists
39and III) the mixed zone where both phases exist simultaneously¹. This selective movement of
40fluids inside the porous media causes unstable displacement that influences the reservoir
41performance^{2,3}. Foam which is a discontinuous gas phase separated by thin liquid films called
42lamellae can decrease mobility ratio between displacing and displaced fluids and address
43gravity segregation⁴⁻⁶. Foam modifies mobility ratio in two ways: first, the relative
44permeability of the displacing fluid (K_{rD}) decreases by trapping gas in porous media, and
45second, by increasing the effective shear viscosity of the displacing fluid (μ_{rD})⁷. Increase
46in apparent viscosity by foam comes from three contributions: (1) surface tension gradient
47created when surfactant foaming agent migrates from the front of the bubbles and
48accumulates at their back, (2) the thin liquid slugs between bubbles, and wall and bubbles,
49and (3) resistance to deformation of air bubbles pass through the porous media that have
50smaller size than foam bubbles⁸. Foam forms inside the porous media by three mechanisms
51leave behind, snap-off, and lamellae division. Leave behind is the dominant mechanism of
52foam generation at lower flow rates. As gas invades into a media saturated with surfactant, the
53lamellae are left behind the gas⁹. Snap off mechanism is more important at high flow rate and

54can reduce the mobility of foam more significantly in comparison to the leave behind
55mechanism. Gas bubble expands as it moves through a pore throat to a pore body causing a
56decrease in capillary pressure and a pressure gradient in the liquid phase. Consequently,
57liquid accumulates in the pore throat and if the capillary pressure is large enough the liquid
58finally snaps off the gas bubble¹⁰. Lamellae division is similar to snap off and occurs at high
59flow rates. As a pre-existing lamellae approaches a branch point in porous media it divides
60into several lamellae¹¹. Foam flows in porous media as a continuous phase or discontinuous
61phase¹². Continuous flow occurs when gas goes through porous media without interruption by
62lamella. In discontinuous mode, gas is transferred as a chain of gas bubbles that are separated
63by lamella.

64Foam can be placed in the reservoir by pre-generated foam injection, co-injection of gas and
65surfactant and surfactant-alternating-gas (SAG) injection. Surfactant must be used as the
66liquid phase to stabilize lamellae. Researches showed SAG injection in which alternating
67slugs of a surfactant solution and gas are injected into the reservoir is the optimum method for
68foam placing into the reservoir¹³⁻¹⁵. It reduces the contact of gas and water in surface facilities.
69More importantly, foam weakens as the gas displaces water from the near well-region and the
70injectivity of gas increases and the possibility of reservoir fracturing decreases^{5, 16}. Holt and
71Vassenden⁶ showed foam injection resulted in higher segregation length (i.e. a longer distance
72over which segregation occurs as a result of gravity) than gas and water. They showed that the
73following equation which was proposed by Stone¹ and Jenkins¹⁷ can be used for calculating

74 segregation length (L_g) in SAG injection process (the distance over which segregation
 75 occurs as a result of gravity):

$$76 \quad L_g = \frac{Q}{K(\rho_w - \rho_g)gD\gamma_{rt}^m} \quad (1)$$

77 where $Q(\frac{m^3}{s})$ is the total volumetric injection rate of gas and liquid, $K(m^2)$ is the

78 vertical permeability of the porous medium, ρ_w and $\rho_g(\frac{kg}{m^3})$ are liquid and gas density

79 respectively, $g(\frac{m}{s^2})$ is the gravity acceleration, $D(m)$ is the thickness of the porous

80 medium, and $\gamma_{rt}^m = \frac{K_{rw}}{\mu_w} + \frac{K_{rg}}{\mu_g}(\frac{1}{Pa.s})$ is the total relative mobility of the mixed gas-liquid

81 zone. Here K_{rw} and K_{rg} are relative permeability of water and gas respectively, and

82 $\mu_w(Pa.s)$ and $\mu_g(Pa.s)$ are the viscosity of water and gas respectively. Shi and

83 Rossen⁵ indicated high value of gravity numbers (e.g. ratio between viscous and gravity

84 forces) defined as $N_g = \frac{\Delta\rho \cdot g}{\nabla p}$ promote gravity segregation in SAG injection process.

85 Here $\nabla p(\frac{Pa}{m})$ is the pressure gradient, $\Delta\rho(\frac{kg}{m^3})$ is the density differences between

86 fluids and $g(\frac{m}{s^2})$ is the gravity acceleration. Some other researchers studied the effect of

87 gravity segregation in SAG injection process¹⁸⁻²². However, they did not consider the effect of

88 fingering of highly mobile gas into the foam bank in their studies. Recently, Farajzadeh et al²³

89 showed in a simulation study that the fingering of highly-mobile gas into the foam bank may
90 be unavoidable and causes instabilities in a foam injection process. This fingering can also
91 distort the foam front, even when favorable mobility control creates in foam front. To the best
92 of our knowledge, there is no experimental study to support these findings or refute them.

93 In this work, fingering of highly mobile gas into the foam bank and gravity segregation effects
94 on fluids separation were studied in a foam injection process using a 2D micromodel system
95 at a wide range of the injection rate.

96 **Experimental Considerations**

97 **Design and fabrication of porous media**

98 Following the procedure described by Osei-Bonsu et al.²⁴, the porous medium used in this
99 research was designed with ‘Rhinoceros’ CAD software package for 3D illustrations. The
100 pore network was created from a Voronoi diagram consisting of 660 polygons. Voronoi
101 diagrams can be used to design homogenous and heterogeneous microfluidic and
102 micromodel network that was used in many theoretical and numerical studies
103 in the field of porous media and also commonly used in the foams literature²⁵⁻²⁷.
104 The model was populated with a random length pore throat size distribution ranging from 0.3
105 to 0.5 mm. The pore throat size can be defined as the radius of a circle fitting in the narrowest
106 space that connect two adjacent pore bodies together. Figures 1 (a), (b) and (c) show the top
107 view of the porous medium, a zoomed portion of the model and the pore throat size
108 distributions of the model, respectively. The dimension of the printed matrix was 110 mm x

10950 mm x 0.25 mm. The model was oil wet and the porosity and permeability of the model
 110were 39.4 % and 10.6 Darcy, respectively. The stereolithographic (STL) file of the CAD
 111model was printed with an acrylic based material (acrylic oligomer) using a high resolution
 112Polyjet 3D printer (Objet 30 pro, Stratasys, UK). The top of the model was sealed with a
 113Plexiglas plate to prevent flow over the grains. Furthermore, two perforations (1 mm
 114diameter) at opposite ends of the porous medium were placed to serve as the inlet and outlet.

115Fluid properties and experimental procedure

116In each run of the experiment, the printed porous medium was saturated with Isopar V
 117(Brenntag, UK) referred to as ‘oil’ hereafter. The oil was stained red in order to enhance the
 118visual contrast. Table 1 shows properties of the oil used in this study.

119Table 1. Properties of the oil together with its surface tension and interfacial tension with the
 120surfactant solution used in the present study^{2, 28}.

Oil	Compositio n	Viscosity (x 10 ⁻³ Pa.s)	Density (g/cm ³)	Surface tension (mN/m)	Interfacial tension (mN/m)
Isopar V	C14-C19	10.84	0.81	25.44	0.13

121The surfactant solution used for foam generation was prepared from a 1:1 blend of sodium
 122dodecyl sulphate and cocamidopropyl betaine (2% active content) with 0.25M NaCl solution.
 123Osei-Bonsu et al.²⁸ showed that this surfactant combination was tolerant to the presence of oil
 124under our experimental conditions. The surfactant solution and nitrogen were injected using a
 125syringe pump (Harvard Apparatus, PhD Ultra) and a mass flow controller (Bronkhorst, UK).

126 Surfactant and gas met before the model and flowed into the model as intermittent slugs of
127 surfactant and gas.

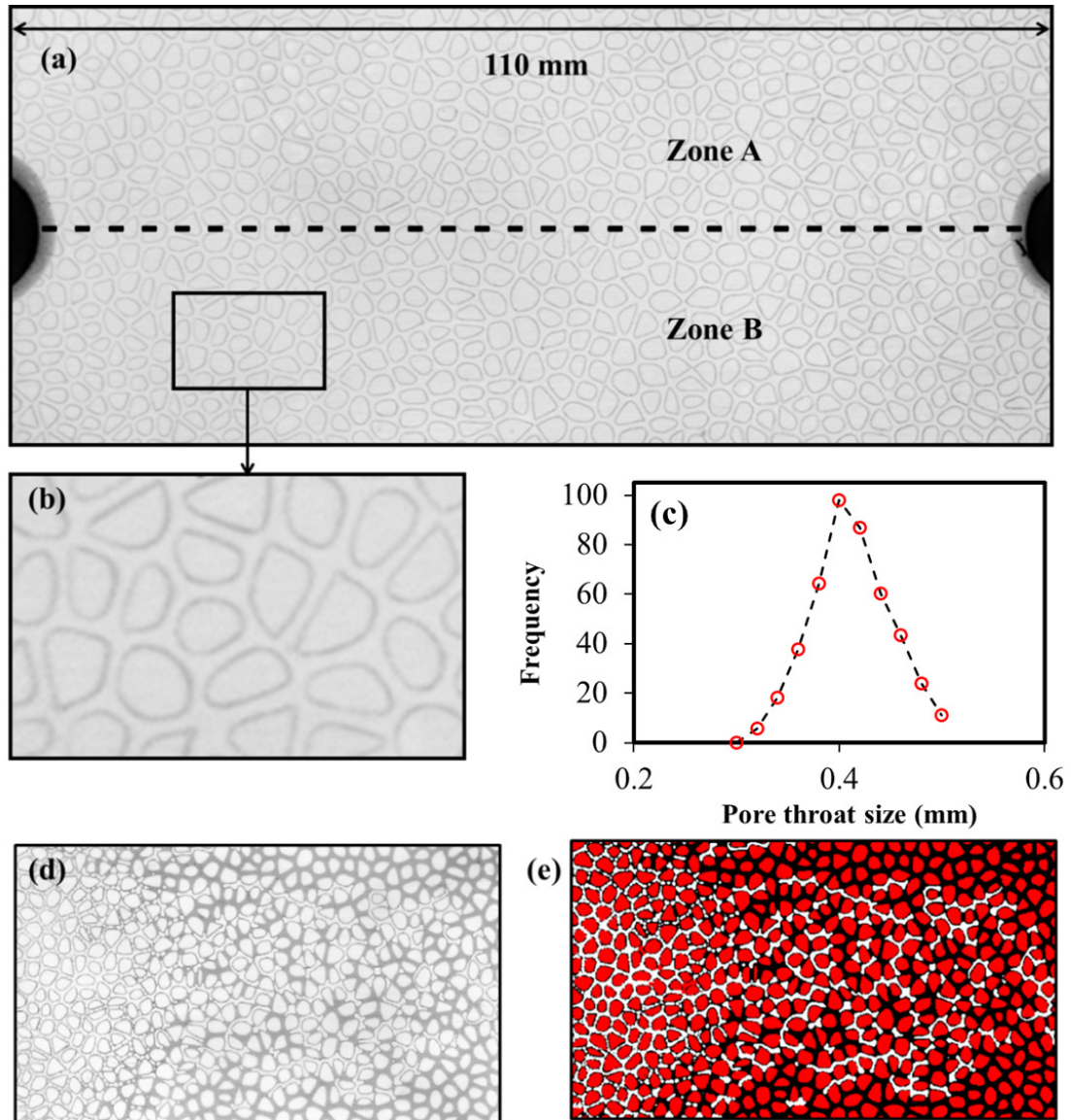
128 A high-resolution digital camera (Teledyne DALSA Genie) controlled by a computer was
129 used to acquire images of the displacement process at regular time intervals. The model
130 porous medium was placed adjacent to a light box to improve the illumination of the captured
131 images. The recorded images had a resolution of 2560 x 2048 pixels with 8 bit gray levels
132 resulting in the pixel size of 40 microns.

133 To understand the effect of fingering of high mobile gas into the foam bank and gravity
134 segregation on fluids separation, we conducted experiments in horizontal and vertical
135 orientations in a printed porous medium. In all experiments, foam was generated in-situ by
136 intermittent injection of gas and surfactant slugs at six flow rates of 1, 5, 10, 20, 40 and 80
137 ml/hr. The fraction of surfactant in injection fluids was 15% of the total volume injected in all
138 experiments. Each run of the experiment was repeated at least three times to ensure the
139 reproducibility of the data. The error bars in the following figures represent the variability in
140 the obtained results for each kind of experiments.

141 **Image analysis**

142 The recorded images were analyzed using in-house codes developed in MATLAB to
143 distinguish the oil, grains (solid phase) and the injected fluids (see Osei-Bonsu et al.²⁴ for
144 details of the segmentation algorithm). Additionally, Image J software was used to determine

145the number of oil blobs due to the fragmentation of the oil phase. Figure 1 (d) and (e)
 146illustrate a typical recorded image and its corresponding segmented image.



147

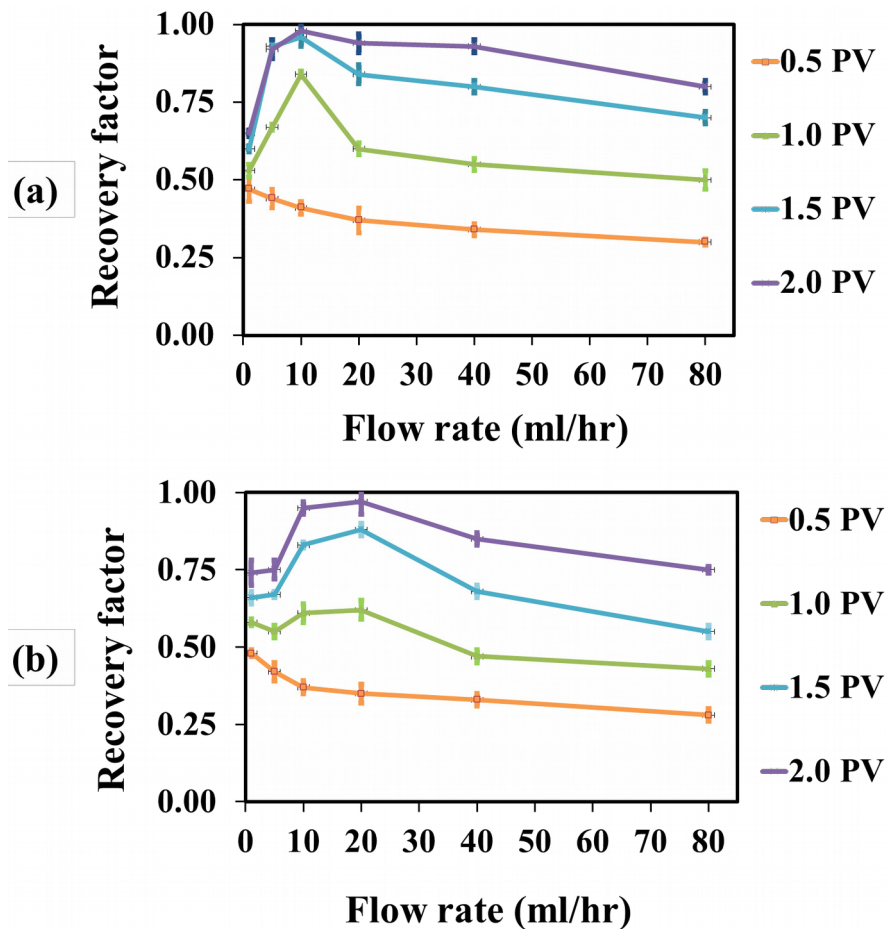
148Figure. 1 (a) Top view of the printed model used in our study. The upper and lower part of the
 149model is referred as Zone A and Zone B in the following analysis. (b) Magnified image of
 150pores to better illustrate the patterns of pores/grains in the printed porous medium (c) Pore
 151throat size distribution of the printed porous medium. (d) A typical image recorded during oil
 152displacement by foam. Dark grey represents oil. (e) The corresponding segmented image of

153the phase distributions presented in (d) with white, black and red representing foam (or
154escaping gas and surfactant), oil and grain respectively.

155RESULTS AND DISCUSSION

156Effects of gas fingering and gravity segregation on foam displacement efficiency

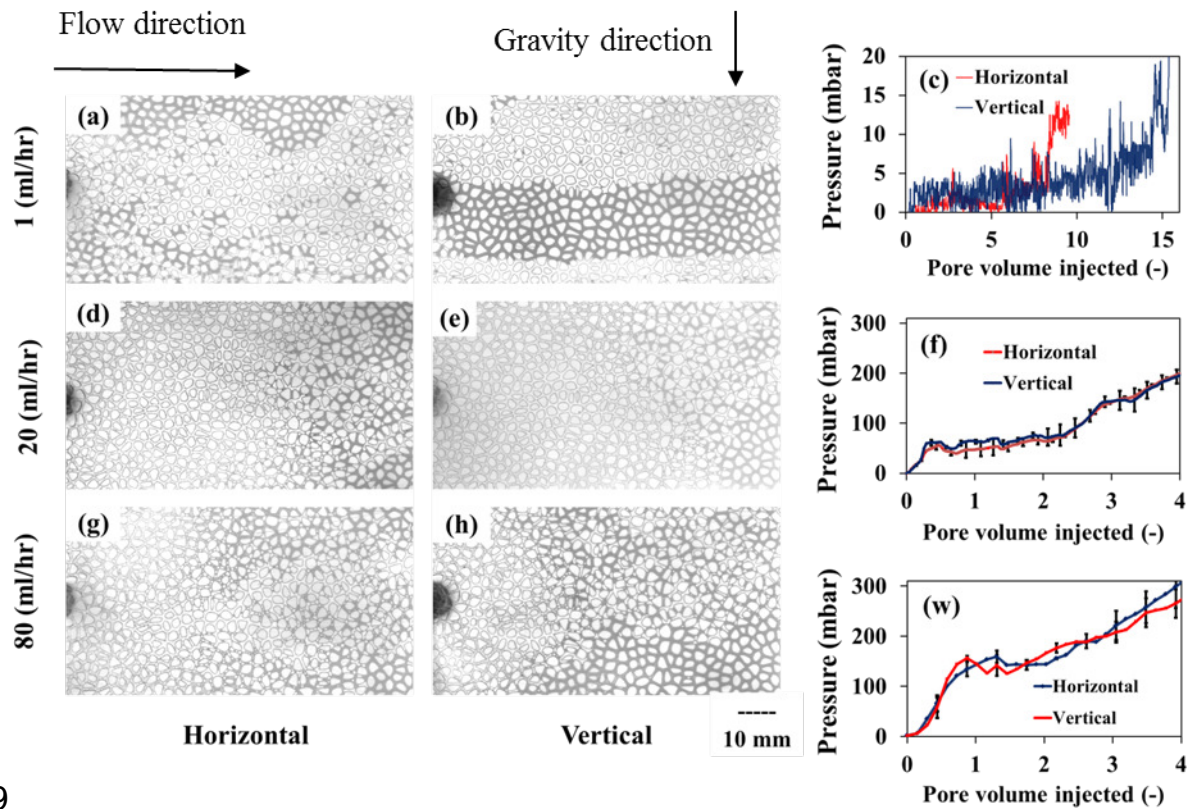
157Figure 2 presents oil recovery in the case of horizontal and vertical orientations at different
158pore volume injected under different injection rates. The recovery factor is defined as the
159fraction of oil initially in place that is produced during the injection process after a given
160number of pore volumes have been injected.



161

162Figure. 2 Oil recovery in the (a) horizontal and (b) vertical orientations, respectively as a
 163function of the flow rate at different pore volume injected indicated in the legend.

164According to the Figure 2, three distinct flow regimes are detectable in both vertical and
 165horizontal orientations depending on the applied injection rate. The characteristics of each
 166flow regime are discussed in the following. For better understanding the nature of each flow
 167regime, phase distribution and pressure drop corresponding to each flow regime are presented
 168in Figure 3.



169

170Figure. 3 Phase distribution in horizontal and vertical orientations at different flow rates. (a),
 171(d) and (g) correspond to the horizontal orientation and (b), (e), and (h) corresponds to the
 172vertical orientation. (c), (f) and (w) illustrate the measured pressures in the case of horizontal
 173and vertical orientation at the flow rate of 1, 20 and 80 ml/hr, respectively.

174 Horizontal orientation

175 Applying low injection rate (1 ml/hr) impacted lamellae generation and mobilization and
176 subsequently displacement efficiency. Visual inspections at this flow regime showed limited
177 rate of lamellae generation. Lamellas were created by leave behind mechanism and snap-off
178 and stayed stagnant. According to Rossen and Gauglitz²⁹ a minimum pressure gradient
179 required for lamellae generation and mobilization that was not achieved initially at this flow
180 regime. It was observed gas tended to be trapped behind lamellae in some point until the
181 pressure drop per lamella built up and passed the threshold for mobilization. After
182 mobilization, the pressure drop of the model decreased and lamellae destruction occurred
183 when the moving lamellae met the oil phase. The fluctuations in the recorded pressures
184 observed in Figure 3 (c) are due to the unsteady state nature of the displacement process (i.e.
185 lamella generation leads to increase the pressure and lamella mobilization and coalescence
186 leads to pressure reduction). Capillary numbers (e.g. ratio between viscous and gravity forces,
187 $Ca = \frac{\mu \cdot v}{\sigma}$) were calculated for each set of experiments in Table 2. Here μ (Pa.s) is the
188 viscosity of the injected fluids (due to most of the injected fluids was gas, viscosity of gas was
189 used in the calculations), v ($\frac{m}{s}$) is the total superficial velocity of the injected fluids, and
190 σ ($\frac{N}{m}$) is the surface tension between gas and surfactant. Low value of capillary number at
191 low flow rate in horizontal orientation is associated with low rate of lamellae generation and
192 mobilization.

193

194

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198

199 Table 2. Capillary numbers for the experiments conducted at different flow rates.

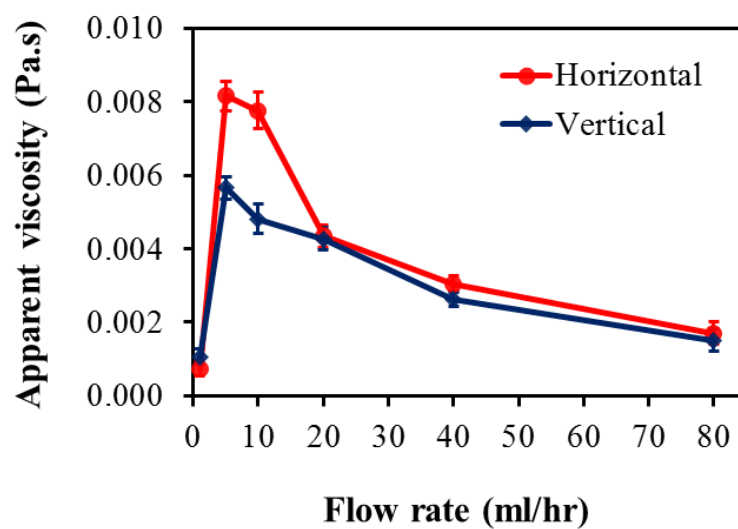
Flow rate (ml/hr)	Ca
1	1.4×10^{-6}
5	7.2×10^{-6}
10	1.4×10^{-5}
20	2.9×10^{-5}
40	5.8×10^{-5}
80	1.1×10^{-4}

200

201 The limited rate of lamellae generation and mobilization and the existence of lamellae

202 destruction resulted in establishing a weak foam in the model. Figure 4 shows low value of

203 apparent viscosity at low flow rate associated to limited rate of foam generation. Full oil
 204 recovery achieved after 10 PV injections and the residing oil displaced mostly by gas and
 205 surfactant instead of foam. High rate of lamellae generation and mobilization was observed
 206 after 6 PV of injection as the pressure gradient increased and the oil saturation decreased.
 207 After adequate fluids injection, the whole model was saturated with foam bubbles. According
 208 to table 2, this flow regime is corresponding to capillary numbers lower than about 1.0×10^{-6} .



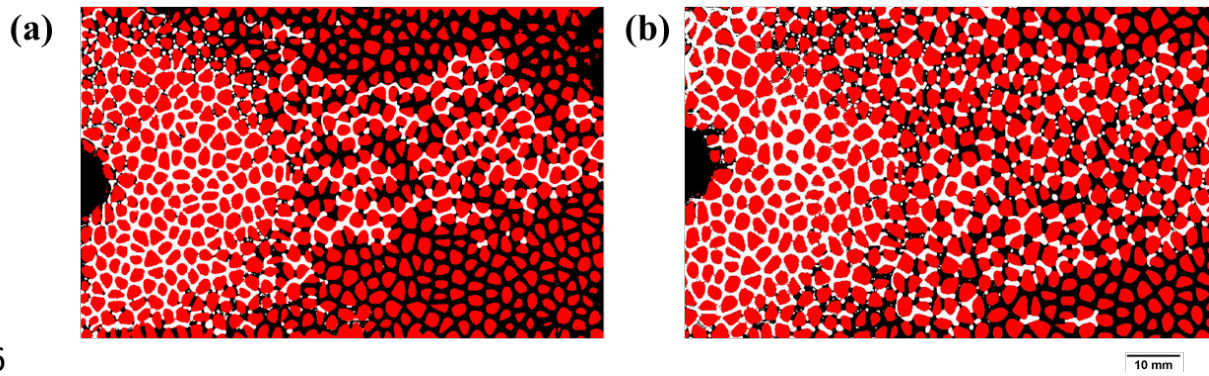
209

210 Figure. 4 The relationship between apparent viscosity of foam and flow rate after 4 PV of
 211 injection process.

212 The second flow regime occurred when the pressure gradient is large enough to produce fine
 213 textured foams generated mostly by snap-off mechanism and lamella division. The rate of
 214 lamellae generation and mobilization was large enough to make strong foam as can be seen in
 215 Figure 4. The gradual increase in the pressure drop and less pressure fluctuations in Figure 3
 216 (f) confirmed strong foam generation. Fingering of the gas phase through the foam bank was
 217 however observed in this flow regime such that a continuous gas phase was formed inside the

218model. In addition, Gas released from foam coalescence fingered through the oil phase in
219front of it and created some isolated oil blobs as can be seen in Figure 3 (d). In this flow
220regime, full oil recovery from the porous medium was attained after approximately 2.5 PV of
221injection.

222At high flow rates, the displacement efficiency of foam injection decreased again as can be
223seen in Figure 2 (a) and Figure 3 (g). This is due to that at higher injection flow rate, more
224volume of gas fingers and subsequently more escaping gas occurred as can be seen in Figure
225. Visual observations also showed the volume of foam that existed as continuous phase
226increases by increasing flow rate. This continuous gas phase eventually fingered through the
227oil phase. Fingering more volume of gas caused instability in the displacement process and
228decrease in displacement efficiency. It may be expected that this gas fingering is due to dry-
229out effect of foam at 85 foam quality. It can be said the dry-out effect is not relevant in our
230system with rather larger pores. Also, Kofi Osei-Bonsu et al ²⁴ used the same surfactant and a
231porous media quite similar to what we used in our study and found the foam quality
232corresponds to the critical capillary pressure was 98. Therefore, we can be sure that in our
233system, it is presumably the presence of oil (rather than the dry out effect) which is what
234helps to destabilise foam. Complete oil displacement was occurred after about 3.5 PV of
235injection at 80 ml/hr flow rate.



236

237 Figure. 5 (a) and (b) show phase distribution for 20 and 80 ml/min gas flow rate respectively I
 238 in horizontal orientation.

239 Vertical orientation

240 Similar to the horizontal orientation, three distinct flow regimes were observed in the case of
 241 the vertical orientation. The first flow regime includes the lower end of injection rates (from 1
 242 ml/hr to 5 ml/hr). Complete segregation of gas and surfactant was the dominant characteristic
 243 of this flow regime as depicted in Figure 3 (b). As Shi and Rossen proposed ⁵ large values of
 244 gravity number imply gravity segregation. Here gravity number ($N_g = \frac{\Delta\rho \cdot g}{\nabla P}$) was
 245 calculated for different flow rates after 1 PV injection in Table 3 for the experiment conducted
 246 in vertical orientation.

247 Table 3. Calculated Gravity number for the experiments conducted at different flow rates in
 248 vertical orientation after 1 PV injection.

Flow rate (ml/hr)	N_g
-------------------	-------

1	1.5×10^{-1}
5	2.7×10^{-2}
10	7.3×10^{-3}
20	4.3×10^{-3}
40	2.4×10^{-3}
80	1.45×10^{-3}

249

250At low flow rate, flow rate was not large enough to provide a proper mixing zone for foam
251generation. Upon entering the model, gravity segregation occurred resulting from the density
252differences between the fluids: gas flowed upward (Zone A) while the surfactant flowed
253downward (Zone B) in the model. Therefore, oil was displaced predominantly by gas in Zone
254A and by surfactant in Zone B. The upper and lower part of the model is referred as Zone A
255and Zone B as depicted in Figure 1 (a). Complete oil recovery was achieved after 16 PV
256owing to the adverse impact of the high gravity segregation on fluids separation. Foam
257generation was started after 12 PV of injection mostly by leave behind mechanism. After
258many pore volume fluids injections, the whole model was saturated with foam. Based on
259Table 3, high gravity segregation occurred at gravity number more than 1.0×10^{-2} .

260The second flow regime corresponds to the intermediate injection rates. According to
261equation (1), increasing flow rate leads to longer mixed zone and thus more foam generation

262 and increase in apparent viscosity of foam as depicted in Figure 4. Segregation length L_g
263 can be estimated by combining Darcy's law with equation (1) which leads to

$$264 \quad L_g = \left(\frac{\Delta P_{Horizontal}}{\Delta P_{Hyd}} \right) \left(\frac{W \cdot D}{L} \right) \quad \text{that } W, D \text{ and } L \text{ are the width, thickness and length of the}$$

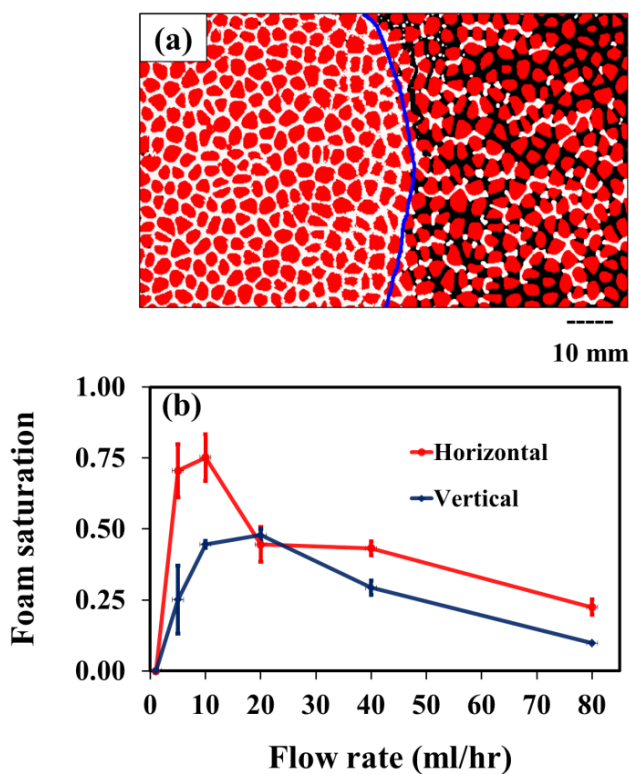
265 porous medium. The hydrostatic pressure ($\Delta P_{Hyd} = \rho g W$) across the model porous
266 medium with $W = 50$ mm in height gives rise to an approximate pressure of 4 mbar. Assuming
267 a horizontal pressure drop of 100 mbar (Figure 3 (f)), the segregation length will be in the
268 order of 3 mm. The recorded images showed that the foam generation mostly occurred at this
269 segregation length followed by foam propagation to other parts of the porous medium as
270 illustrated in Figure 3 (e). Beside foam generation in the mixed zone, the movement of gas to
271 Zone A and surfactant to Zone B was observed. The accumulation of surfactant in Zone B
272 provided suitable condition for generating lense in Zone B by leave behind mechanism.

273 The third regime in the case of vertical orientation corresponds to the higher injection rates.
274 In this flow regime, foam was generated in the mixed zone. However, similar to horizontal
275 orientation, fingering of high volume of gas had adverse effect on foam displacement as can
276 be seen in Figure 3 (h). Although, higher flow rates helped with addressing the effect of
277 gravity segregation, but displacement efficiency decreases due to gas viscous fingering.

278 **Quantitative analysis on foam saturation**

279 The analysis presented above highlighted the adverse effect of gas fingering and fluids
280 separation by gravity segregation on foam bank saturation. Our recorded images of oil

281displacement by foam in porous media enabled us to measure the area of porous media
 282saturated by foam. Figure 6 (b) illustrates foam saturations at different flow rates after 1.2 PV
 283injections for both horizontal and vertical orientations. Foam saturation was calculated by
 284dividing the area occupied by foam to the total area of the pore space. The recorded images
 285were segmented to calculate the area covered by the foam bubbles. A typical example of the
 286segmented image is illustrated in Figure 6 (a). The solid blue line in Figure 6 (a) indicates the
 287foam front. The white color to the right side of the foam front corresponds to the gas phase
 288escaping out of foam due to gas fingering or the coalescence of foam bubbles by oil which
 289was not included in the calculation of foam saturation.



290

291Figure. 6 (a) A typical segmented image used for calculating the saturation of foam. Red,
 292black and white indicate the grains, oil and foam (and escaping gas) respectively. This image
 293corresponds to the case of 10 ml/hr injection rate in the horizontal orientation. (b)

294 Relationship between the flow rate and foam saturation after 1.5 PV injection of gas and
295 surfactant solution for the horizontal and vertical orientation. The error bars indicate the
296 standard deviation over 3 repeat measurements.

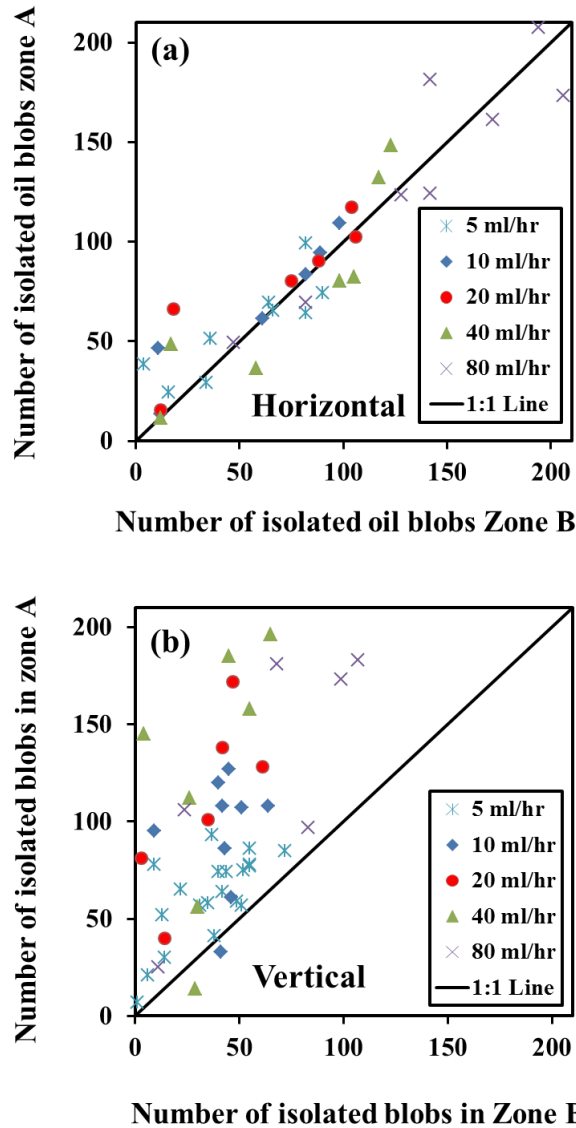
297 In the horizontal orientation, after 1.2 PV injection and when the injection rate is low (first
298 flow regime), due to low rate of lamellae generation and mobilization and existence of
299 lamellae destruction there was no foam and hence foam saturation was zero. Then foam
300 saturation increased in the second flow regime (the intermediate stage) to about 75 percent as
301 foam generation by snap off mechanism increased. In the third flow regime, the saturation of
302 foam influenced by gas fingering and decreased to about 25 percent.

303 In the vertical orientation, the saturation of foam was zero in the first flow regime (when the
304 injection rate is low) due to complete segregation of gas and surfactant. In the second flow
305 regime, the effect of gravity segregation decreased by increasing flow rate leading to
306 increasing foam saturation (around 50 percent) followed by the third flow regime (when the
307 injection rate is high) where the saturation of foam decreases to about 15 percent resulted
308 from gas fingering.

309 **Effects of the injection rate and gravity segregation on oil entrapment**

310 Our results indicated that gas fingering and fluids separation by gravity segregation has
311 significant impact on the oil entrapment and spatial distribution of the oil blobs during foam
312 flooding in porous media. Using the recorded images, we computed the number of

313 disconnected oil phase in Zone A and Zone B (defined in Figure 1) with the results presented
 314 in Figure 7.



315

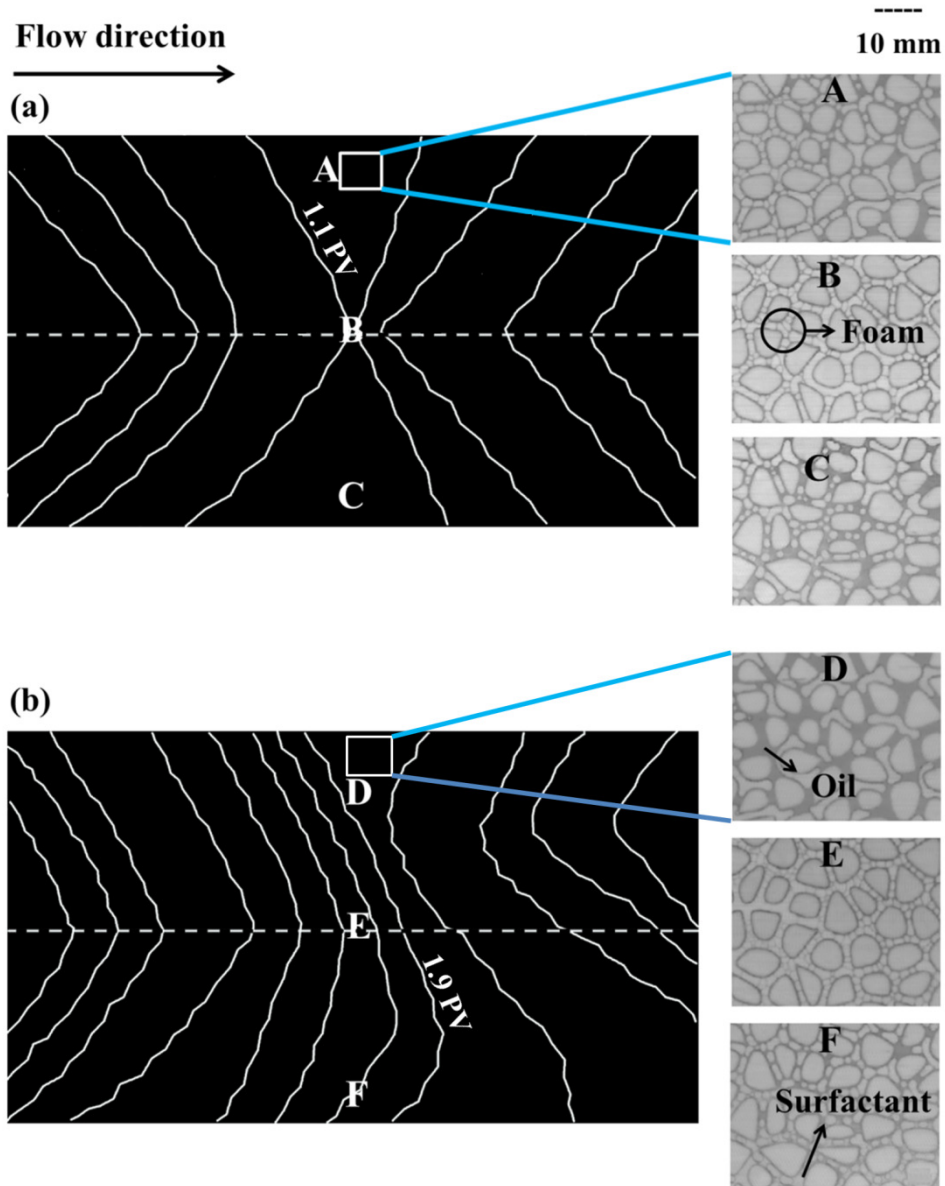
316 Figure. 7 The relationship between the number of trapped oil blobs in Zone A and Zone B in
 317 (a) horizontal and (b) vertical orientation, respectively. The legend indicates the applied
 318 injection rates.

319 Figure 7 (a) shows the oil blob distribution through the horizontal model porous medium is
 320 almost homogenous with nearly similar number of isolated oil blobs distributed in Zone A

321and Zone B (defined in Figure 1). However, this is not the case when the porous medium is
322placed vertically with most of the blobs trapped within Zone A (i.e. the upper part of the
323porous medium). As already illustrated, during injection through the vertical oriented porous
324medium, gas and surfactant solution moved to Zone A and Zone B, respectively due to the
325gravity segregation. Since the viscosity contrast between gas and oil is greater than viscosity
326contrast between surfactant and oil, Zone A is more prone to fingering and formation of
327isolated oil blobs. One can add to this the contribution of the fraction of gas escaping from
328Zone B toward Zone A due to the gravity.

329Dynamics of foam displacement influenced by the gravity

330In addition to the number and distribution of oil blobs, oil recovery and foam saturation,
331gravity segregation influences the dynamic of foam front displacement. As an example,
332Figure 8 qualitatively shows the patterns and dynamics of foam front displacement at 10 ml/hr
333injection rate in the case of horizontal and vertical porous medium.



334

335 Figure. 8 The interface (white line) between invaded and uninvaded area at the equal pore
 336 volume injected intervals of 0.2 in the porous medium placed (a) horizontally and (b)
 337 vertically. The interface propagates from left to right. The first interface at the left side of the
 338 figure corresponds to 0.5 PV injected. The injection rate in both cases was fixed at 20 ml/hr.
 339 The dashed line is the boundary between Zone A and Zone B. The insets illustrate typical
 340 examples of phase distribution at upper, middle and lower parts of the porous medium.

341 During oil displacement in horizontal orientation, the front had a convex shape up to 1.2 PV
342 injection followed by a gradual evolution into a concave front. The morphological evolution
343 of the front is likely due to variations in the foam texture along the front. The insets in Figure
344 illustrating typical phase distribution patterns at the upper, middle and lower regions of the
345 porous medium placed horizontally shows that the bubble density in the middle region is
346 higher than upper and lower regions. Higher bubble density decreases the mobilization of
347 foam bubbles in the middle section of the model thus diverting the flow to the upper and
348 lower regions which causes the change in the morphology of the front.

349 In vertical orientation, foam front adopted an ‘S’ shape after 1.7 PV injections. This is due to
350 the gradual increase of the bubble density in the middle region and that a small part of Zone
351 A caused high flow resistance (this is once again due to high bubble density) and changed
352 flow orientations to other parts of the model. Subsequently, the foam front propagation in
353 Zone B was faster than Zone A due to the presence of more liquid in Zone B (higher
354 saturation) compared to Zone A as a result of the gravity segregation which led to a decrease
355 in flow resistance in that region.

356 **Summary and conclusions**

357 This study set out to investigate the effects of fingering of highly mobile gas into the foam
358 bank and gravity segregation on fluids separation on the performance of foam injection
359 process. A comprehensive series of foam injection experiments were conducted in both
360 horizontal and vertical orientations in a porous medium fabricated by 3D printing technology
361 in the presence of oil. In horizontal orientation, obtained results showed lamellae generation

362and mobilization was not large enough at capillary number below 10^{-6} to generate strong
363foam. Increasing flow rate led to generation of fine textured foam by snap off mechanism.
364However, gas fingering into the oil bank influence foam injection process and had adverse
365effect on displacement efficiency at higher flow rate. In vertical direction, complete
366segregation of gas and surfactant occurred at gravity number higher than 1.0×10^{-2} . A rise in
367flow rate led to increase in foam generation in the mixed zone and addressing gravity
368segregation. However, gas viscous fingering at high flow rates resulted in a decrease in foam
369sweep efficiency. These findings highlight the significant adverse impact of gas fingering and
370gravity segregation on foam performance echoing the necessity to include these phenomena
371when investigating flow displacement by foam in porous media.

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