



HAL
open science

Effect of grain shape on quasi-static fluid-fluid displacement in porous media

Zhongzheng Wang, Jean-Michel Pereira, Yixiang Gan

► **To cite this version:**

Zhongzheng Wang, Jean-Michel Pereira, Yixiang Gan. Effect of grain shape on quasi-static fluid-fluid displacement in porous media. *Water Resources Research*, 2021, 10.1029/2020WR029415 . hal-03177573

HAL Id: hal-03177573

<https://enpc.hal.science/hal-03177573v1>

Submitted on 23 Mar 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Effect of grain shape on quasi-static fluid-fluid displacement in porous media

Zhongzheng Wang^{1,2}, Jean-Michel Pereira², and Yixiang Gan^{1,3}

¹School of Civil Engineering, The University of Sydney, NSW 2006, Australia.

²Navier, Ecole des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France.

³The University of Sydney Nano Institute (Sydney Nano), The University of Sydney, NSW 2006, Australia

Key Points:

- A novel pore network model algorithm is developed to probe the effect of grain shape on multiphase displacement in porous media.
- Systematic simulations are conducted using the proposed algorithm across a wide range of wetting conditions and particle shapes.
- Through analyzing various metrics during displacement, the results highlight the profound influence of particle shape on multiphase flow.

Corresponding author: Yixiang Gan, yixiang.gan@sydney.edu.au

Abstract

We study how grain shapes impact multiphase flow in porous media in the quasi-static regime using an extended pore-network model. The algorithm allows the explicit determination of different types of pore-scale instabilities and tracks the interface motion during fluid-fluid displacement process. It also includes the volume capacitance model, such that both the evolution of capillary pressure signal and sizes of Haines jumps can be captured. Further, it considers the pinning of menisci at sharp edges of grains, through which the distribution of effective contact angles can be obtained. Simulations are carried out across a wide range of wetting conditions for different particle shapes. Our results show that the effective contact angle distribution during displacement widens as the grain becomes more angular, which consequently modifies the macroscopic fluid invasion morphology. By analyzing various characteristic metrics during displacement, including capillary pressure signal, Haines jump size distribution, and fractal dimension, our results highlight the profound influence of particle shape on the multiphase flow.

1 Introduction

Fluid-fluid displacement in porous media is a common phenomenon encountered in a wide range of natural and industrial processes, such as water infiltration into soil (Lipiec et al., 2006), carbon sequestration (Szulczewski et al., 2012; Matter et al., 2016), enhanced oil recovery (Lake et al., 2014; M. Blunt et al., 1993), and remediation of contamination in aquifer systems (Nadim et al., 2000). As indicated by the pioneering works by Lenormand et al (Lenormand et al., 1988; Lenormand & Zarcone, 1989), the multiphase displacement patterns strongly depend on the capillary number (i.e., relative strength of viscous force to capillary force) and the viscosity ratio of the two fluids, and a phase diagram including capillary fingering, viscous fingering, and stable displacement was presented. Since then, extensive efforts have been devoted to further investigation of how fluid properties, flow conditions, and topological characteristics of the porous media modify the invasion morphology (Yortsos et al., 1997; Armstrong et al., 2014; Rabbani et al., 2018; Holtzman, 2016; Wang et al., 2019; Hu et al., 2019; Ju et al., 2020; Xu et al., 2014). Specifically, both numerical and experimental works have revealed the profound influence of wettability (i.e., contact angle) in two phase flows (Crisp & Thorpe, 1948; Purcell, 1950; Mason & Morrow, 1994; Cieplak & Robbins, 1990; Trojer et al., 2015; Jung et al., 2016; Wang et al., 2019, 2020; Holtzman & Segre, 2015; Zhao et al., 2016; Ran et al., 2018; Primkulov et al., 2018). However, the effective contact angle, as one of the key controlling factors, is often unknown prior to the displacement process due to the complex geometry of pore space. Even for chemically homogeneous porous media, a wide distribution of contact angles have been observed due to roughness and pinning of menisci at sharp edges (AlRatrou et al., 2018; M. J. Blunt et al., 2019, 2021). Therefore, it is important to understand how particle shape affects the effective contact angles, which can consequently alter the pore-scale instability events and macroscopic invasion morphology (Cieplak & Robbins, 1990; Holtzman & Segre, 2015; Geistlinger & Zulfikar, n.d.; Zulfikar et al., n.d.; AlRatrou et al., 2018).

In the quasi-static regime of multiphase flow where capillary force dominates the displacement, various numerical approaches have been developed to supplement experiments, including Navier-Stokes equation solvers and pore-network models. The methods of the latter category have been successfully applied in investigation of macroscopic invasion patterns due to significantly less computational cost (M. J. Blunt, 1998, 2001; Cieplak & Robbins, 1988, 1990; Holtzman & Segre, 2015; Holtzman, 2016; Primkulov et al., 2018; Hu et al., 2019). A subclass of pore-network models, the interface tracking algorithm, initially proposed by Cieplak and Robbins (Cieplak & Robbins, 1988, 1990) and recently extended by Primkulov et al. (Primkulov et al., 2018) for consideration of corner flow, has been found successful in reproducing multiphase displacement experiments in Hele-Shaw cells (Chapuis et al., 2008; Trojer et al., 2015; Holtzman & Segre,

2015; Holtzman, 2016; Zhao et al., 2016; Ran et al., 2018). This method captures the pore-scale invasion mechanisms by taking into account the local pore geometry, including the cooperative pore-filling event, which stabilizes the invasion during imbibition (Cieplak & Robbins, 1988, 1990; Holtzman & Segre, 2015). However, up to now, this type of pore-network models is applicable to perfectly spherical particles, whereas grains with irregular shapes are prevalent in natural systems such as sand packs, and solid walls characterized by surface with sharp edges due to manufacture limitations are encountered in microfluidics. These non-smooth surfaces can often lead to pinning of menisci during displacement process, which results in effective contact angles deviating from the intrinsic one, altering the capillary resistance at local pore/throat. It is worth noting that surface roughness has also proven influential on the effective contact angle during fluid-fluid displacement process (Mehmani et al., 2019; Zulfiqar et al., n.d.; AlRatrouf et al., 2018; Chen et al., 2018). One option to distinguish the impact from particle shape and roughness on contact angle is whether the effect is transient. Due to surface roughness, the effective contact angle can change as the liquid fills the grooves of the surface, leading to a time-dependent behaviour of contact angle. This phenomenon has been extensively observed in experiments (Mishra et al., 2016; Moulinet & Bartolo, 2007; Sbragaglia et al., 2007; Seo et al., 2018; Papadopoulos et al., 2013), where the effective contact angle could be described by the Wenzel or Cassie-Baxter model, depending on the wetting states (Wenzel, 1936; Cassie & Baxter, 1944; Marmur, 2003; Gao & Yan, 2009). On the other hand, the pinning of the meniscus at sharp edges (Gibbs, 1961; Oliver et al., 1977), is a thermodynamically stable configuration. In the current study, we thus focus on the latter phenomenon in the quasi-static displacement process.

Here, we develop an extended pore-network model (called EPONM) to probe the effect of particle shape on quasi-static fluid-fluid displacement. The model incorporates the explicit determination of basic pore-scale instabilities based on the work of Cieplak and Robbins (Cieplak & Robbins, 1988, 1990). It also includes the volume capacitance model (Måløy et al., 1992; Furuberg et al., 1996), which allows us to capture both the evolution of capillary pressure signal and sizes of Haines jumps. Different from the original algorithm where the volume capacitance is a prescribed constant (Måløy et al., 1992; Furuberg et al., 1996), it is calculated based on local pore geometries without extra assumptions. More importantly, the sharp edge pinning effect is added to consider the pinning of the menisci (Gibbs, 1961; Oliver et al., 1977). Our results for different grain shapes indicate that increase in angularity leads to wider distribution of contact angles, which explains the observed greater fluctuations in capillary pressure. Besides, it is found that comparing with more spherical particles, the mean capillary pressure for angular grains is greater in drainage whereas smaller in imbibition. We quantify and analyze the correlation between grain shape and size distribution of Haines jumps, interfacial length, and fractal dimension across a wide range of wetting conditions. The implications of our findings are then discussed.

2 Extended Pore-Network Model

To model the 2D flow patterns observed in Hele-Shaw cells filled with vertical posts (Zhao et al., 2016; Trojer et al., 2015; Hu et al., 2019; Primkulov et al., 2018) with controlled particle shapes, the porous medium is represented by polygons (instead of circles in past studies) placed on two-dimensional triangular lattice. The invading fluid is injected from the center of the simulation domain. Based on a purely geometrical extension of Young-Dupre equation (Gibbs, 1961; Oliver et al., 1977), the equilibrium state of effective contact angle θ measured within the invading fluid at the triple line follows:

$$\theta_0 \leq \theta \leq \theta_0 + (180^\circ - \alpha), \quad (1)$$

where θ_0 and α are the intrinsic contact angle and the angle subtended by the two surfaces forming the edge, respectively (Fig. 1(A)). Since in this work the focus is placed

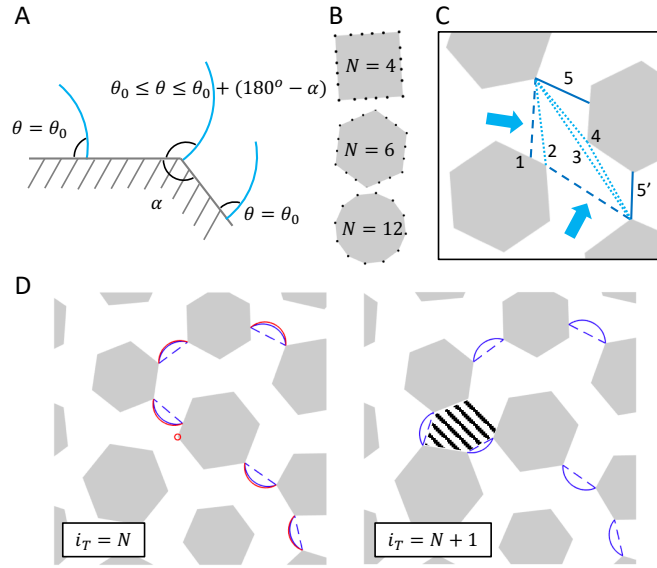


Figure 1. (A) Pinning of menisci at corners leads to greater effective contact angle. (B) Investigated grain shapes in this work with different number of edges N . The black dots represent the mesh points. (C) Schematic showing different invasion types. $\{1-2, 2-3, 3-4, 4-5(5')\}$ correspond to $\{\text{unpin, overlap, touch, unpin}\}$ events, respectively. Blue arrows mark the movement direction of menisci. (D) Snapshots of invasion morphology at two consecutive steps. Blue solid lines represent menisci after relaxation of previous step. Red solid lines represent menisci at the critical state (in this case an unpin event marked by the red circle will take place). The shaded area is invaded, accompanied by retraction of menisci from red lines at $i_T = N$ to blue lines at $i_T = N + 1$.

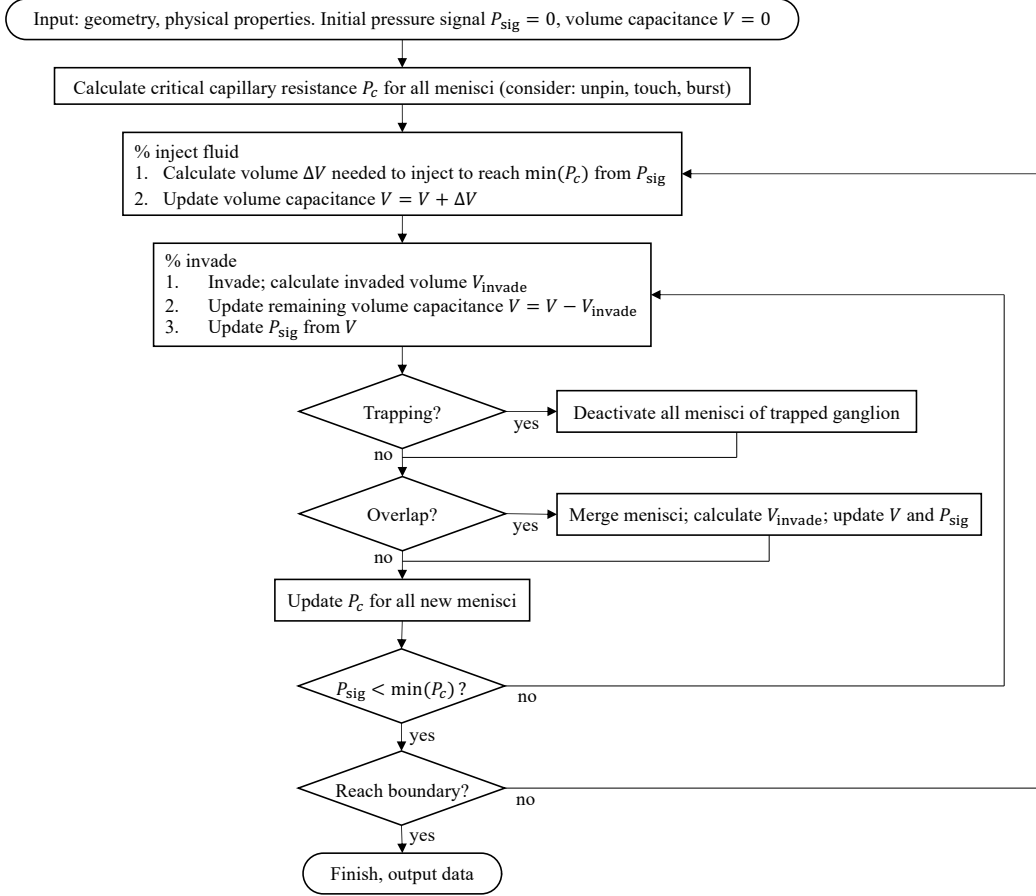


Figure 2. Flow chart of the pore-network model.

117 on the regime of quasi-static displacement, the advancement of liquid front is governed
 118 by capillary force, and the viscous effect is ignored.

119 In the framework of interface tracking algorithm, the menisci move forward through
 120 two types of advancements: (1) pressure-driven events and (2) spontaneous events (re-
 121 laxation). With a constant injection velocity boundary condition, the capillary pressure
 122 builds up accompanied by change in shapes in menisci, until either the meniscus jumps
 123 towards the next mesh point due to the local contact angle being greater than the up-
 124 per bound according to Eqn. 1 (*unpin* event), or the meniscus touches other grain, form-
 125 ing two new menisci (*touch* event). Regarding the fineness of the mesh, the number of
 126 mesh points needed per edge is denoted by $M = E/N$, with E the effective number of
 127 mesh points per grain and N the number of edges a grain has. It is found that $E = 24$
 128 is sufficient for the studied grain shapes, leading to the corresponding number of mesh
 129 points per edge $M = 6, 4, 2$ for square, hexagon, and dodecagon, respectively (Fig. 1(B)).
 130 This is verified by checking both the macroscopic invasion morphology and pore-scale
 131 instability events (see Supporting Information for the mesh sensitivity test). After each
 132 pressure-driven event, the newly invaded area is subtracted from the total volume cap-
 133 acitance (Måløy et al., 1992; Furuberg et al., 1996) (area between red and blue-dashed
 134 lines in Fig. 1(D)), from which the pressure within the invading fluid is updated accord-
 135 ing to the remaining volume capacitance, i.e., redistributing the total volume back to each
 136 active meniscus assuming all are at thermodynamic equilibrium, i.e., all have the same
 137 curvature. Then, potential *overlap* event and further advancement events including *un-*

138 *pin* and/or *touch* are checked and executed. This process is carried out until the small-
 139 est capillary resistance at the invasion front is greater than the remaining pressure within
 140 the invading fluid. Note that after each time step, trapping is checked and all menisci
 141 that belong to trapped regions are deactivated to prevent any further movement. Fig. 1(C)
 142 shows the schematic of several advancement steps initialized by a pressure-driven *un-*
 143 *pin* event. Fig. 1(D) shows local snapshot of invasion morphology at two consecutive time
 144 steps. The blue-solid lines denote the menisci shape after the previous relaxation step,
 145 and red-solid lines denote the menisci shape associated with the next minimum critical
 146 capillary pressure. The flowchart of the algorithm is shown in Fig. 2. More details on
 147 the algorithm, such as the calculation of critical capillary pressure, determination of in-
 148 stability modes, and conversion between pressure and volume can be found in Support-
 149 ing Information.

150 To investigate the effect of particle shapes, squares, hexagons, and dodecagons were
 151 chosen as representative grains with decreasing angularity (Fig. 1(B)). The 1-by-1 rect-
 152 angular simulation domain contains in total 7520 particles placed on triangular lattice,
 153 corresponding to 94 columns of 80 vertically aligned grains with constant porosity of $0.5912 \pm$
 154 0.0005 (see a sample packing structure in Fig. 3(A)). Disorder is introduced by (i) in-
 155 ducing 10 percent variation in particle size with a uniform distribution and (ii) random
 156 rotation of particles in $[0^\circ, 360^\circ)$. The capillary pressure signal, total injected fluid vol-
 157 ume (area in 2D), and size of Haines jump are recorded at each step, until the invasion
 158 front reaches the boundary. Simulations were carried out for each particle shape with
 159 five randomly generated porous media under contact angles ranging from 45° to 165°
 160 with 15° increment. For displacement processes with contact angles below 45° , the 3D
 161 phenomenon corner flow starts to appear (Zhao et al., 2016; Primkulov et al., 2018), which
 162 is currently not captured in the model, and thus those processes are not covered in the
 163 present work.

164 A typical evolution of the invasion front until breakthrough for hexagonal grains
 165 with an intrinsic contact angle of $\theta_0 = 120^\circ$ is shown in Fig. 3(A). Crimson represents
 166 the initial stage whereas yellow indicates the late times. The displacement pattern con-
 167 tains rather ramified structures with significant trapping, which represents the capillary
 168 fingering in drainage. Fig. 3(B-i) shows the evolution of the dimensionless capillary pres-
 169 sure calculated as the curvature $P_c^* = 1/r^*$, with r^* being the radius of the meniscus.
 170 The pressure-driven events and spontaneous events are marked by red circles and yel-
 171 low cross, respectively. Clearly, multiple spontaneous events can take place following a
 172 pressure-driven event, which is a manifestation of a Haines jump. In the limit of van-
 173 ishing capillary number, Haines jump can be regarded as effectively instantaneous compar-
 174 ed with the speed of fluid injection at the inlet. Thus, after conversion from step into
 175 time, which is expressed as volume of injected area normalized by the average pore area,
 176 Fig. 3(B-ii) shows the pressure signal as a function of A_{inj}^* . The P_c^* values at same in-
 177 vasion progress are marked by the same number in Fig. 3(B-i) and Fig. 3(B-ii). Specif-
 178 ically, the processes marked by (1-2) and (2-3) represent a fast Haines jump accompa-
 179 nished by drop in pressure, and slow injection of invading fluid until the next critical P_c^*
 180 is reached, respectively. Fig. 3(B-iii) shows P_c^* signal for the whole simulation. Similar
 181 pressure signal signatures in a stick-slip manner have been observed in experiments at
 182 quasi-static condition (Måløy et al., 1992; Furuberg et al., 1996; Moura et al., 2020).

183 3 Results and Discussion

184 The phase diagram of the displacement patterns across a wide range of contact an-
 185 gles for different particle shapes is shown in Fig. 4(A). The invasion morphology for medium
 186 with dodecagons at $\theta_0 = 45^\circ$ is compact with rather smooth front. This hexagonal shape
 187 is a direct result of the grain placement in the triangular lattice, which has been observed
 188 in previous study (Lenormand, 1990; Holtzman, 2016). However, with increase in an-
 189 gularity, despite the displacement pattern is still relatively stable without trapping, the

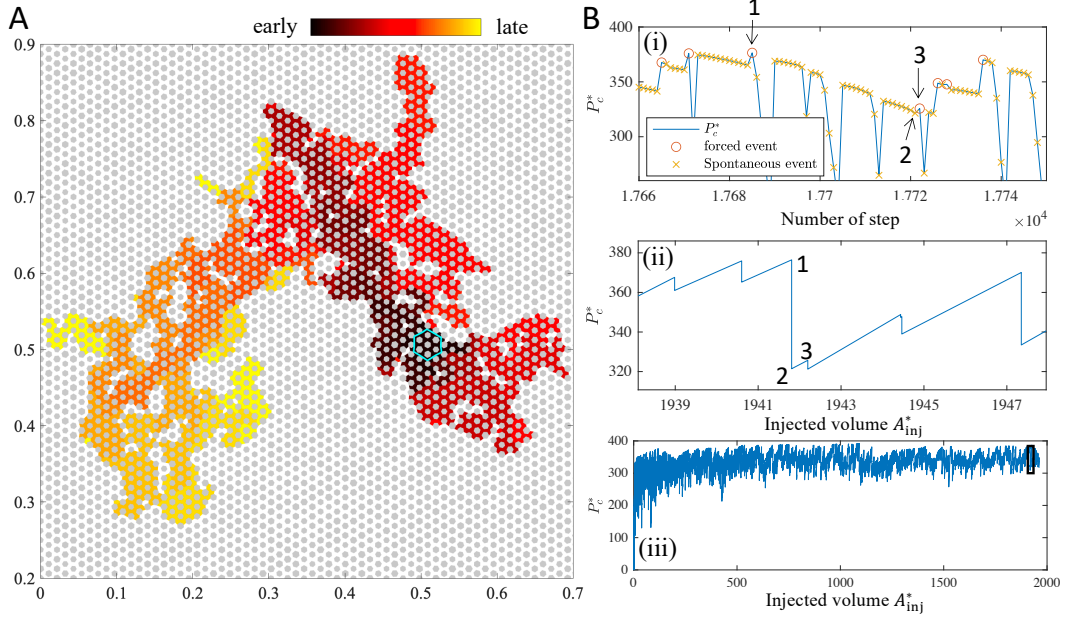


Figure 3. (A) Invasion morphology with hexagon grains (Number of edges $N = 6$) and $\theta_0 = 120^\circ$. The color represents displacement patterns at different steps. The initial positions of menisci are shown as cyan lines. (B) Process of capillary pressure signal: (i) Evolution of dimensionless capillary pressure calculated as the local curvature $P_c^* = 1/r^*$ in terms of number of step. Red circle marks the critical capillary pressure, where the pressure-driven advancement occurs. Yellow crosses represent the consequent spontaneous events (relaxation). (ii) Conversion from step into time expressed in terms of injected fluid area A_{inj}^* which is normalized by the average pore area. The time for Haines jump is regarded as instantaneous, i.e., only the start and end of P_c^* are “felt” at the inlet. The P_c^* values at same invasion progress are marked by the same number in (i) and (ii). (iii) Capillary pressure signal during the whole simulation. The black box is (ii).

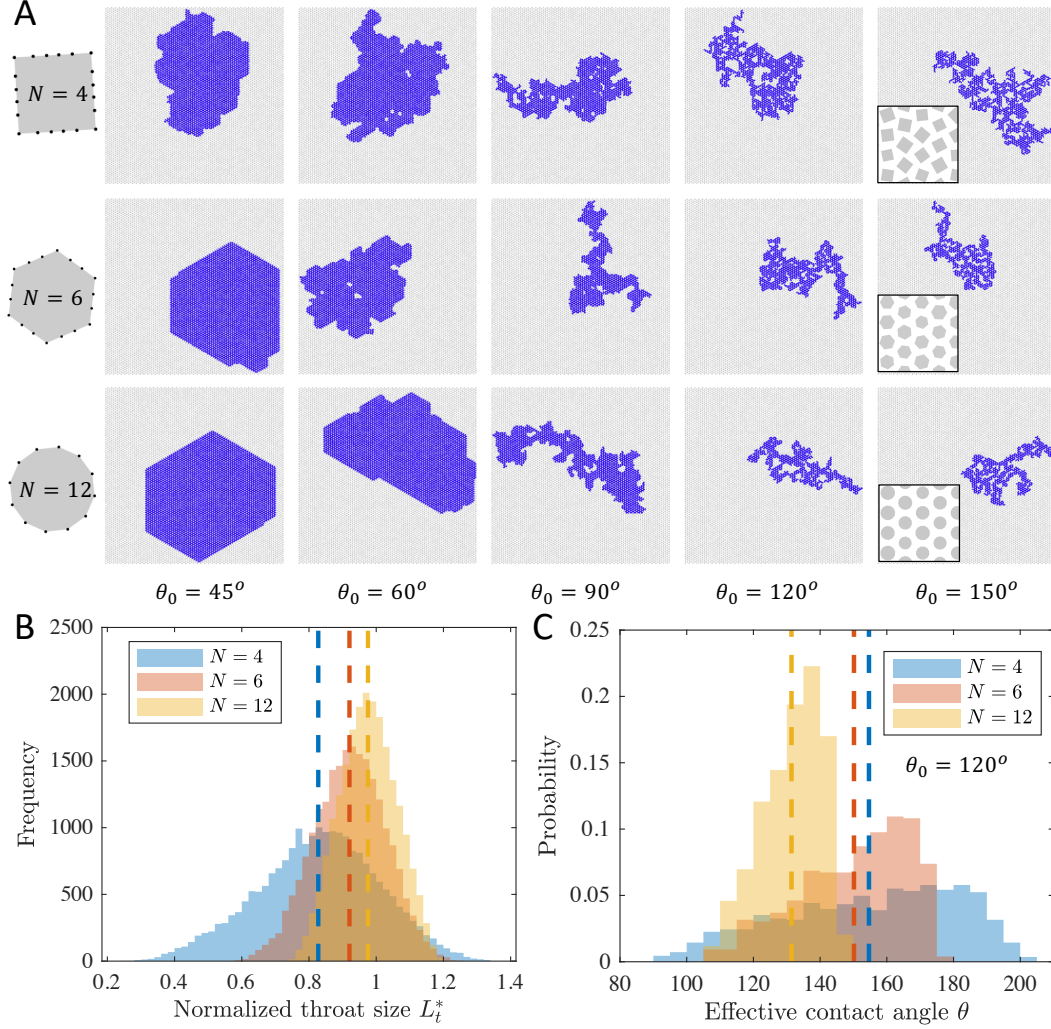


Figure 4. (A) Displacement patterns at the end of the simulation for different wettability conditions and grain shapes. Blue color represents the invading fluid injected from the center of domain. Grey color represents grains. Insets in the last column show the typical grain arrangement of a zoomed region. The simulation ends when the invading fluid reaches the boundary. (B) Distribution of normalized throat size for a typical set of porous media of different grain shapes, calculated as the shortest distance between adjacent grains divided by the throat size of volume equivalent spheres. (C) Contact angle distribution of one typical simulation at the end of simulation with an intrinsic contact angle $\theta_0 = 120^\circ$ for different grain shapes. The dashed lines marks the average value for the corresponding data.

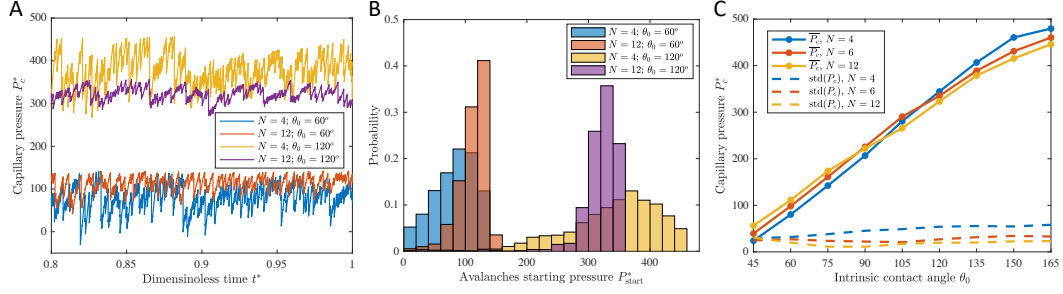


Figure 5. (A) Capillary pressure signals P_c^* for media with squares and dodecagons at $\theta_0 = 60^\circ$ and $\theta_0 = 120^\circ$. Only last 20 percent of invasion is plotted for visualization purpose. (B) Corresponding avalanches starting pressure P_{start}^* distribution for cases in (A), which is the P_c^* at pressure-driven event (red circle in Fig. 3(B-i)). (C) Mean and standard deviation in P_c^* for all grain shapes and wettability conditions. Values are calculated from five individual simulations.

190 invasion front becomes more irregular, indicating a shift of the dominance of local pore
 191 geometry from lattice structure towards grain shape. The results at $\theta_0 = 60^\circ$ demon-
 192 strate similar trend, with trapping events starting to occur for angular grains. With the
 193 increase of θ_0 , the displacement patterns experience a transition from compact displace-
 194 ment to capillary fingering. The distribution of the normalized throat size L_t^* , calculated
 195 as the shortest distance between adjacent grains divided by the throat size of the volume-
 196 equivalent spheres, is shown in Fig. 4(B). Although the media have similar grain size dis-
 197 tribution (10 percent variation with uniform distribution) and arrangement (placed on
 198 triangular lattice), the L_t^* distribution varies drastically for different grain shapes, with
 199 wider span for more angular grains, similar to the effect from increasing topological dis-
 200 order (Wang et al., 2019). Another influence of particle shape is the smaller average throat
 201 size as angularity increases, despite almost constant porosity. For media filled with do-
 202 decagons, the average throat size is close to 1, i.e., the average throat size is similar to
 203 media with perfect spheres, which implies that the shape of dodecagons can be regarded
 204 as very close to spherical particles. Fig. 4(C) shows the effective contact angle distribu-
 205 tion θ at the end of displacement (after the final relaxation process when invasion front
 206 reaches the boundary) for the case with an intrinsic contact angle $\theta_0 = 120^\circ$. Note that
 207 there is one effective contact angle per triple line (and thus two per meniscus). Due to
 208 the sharp edge pinning effect, the distribution narrows for grains with decreasing angu-
 209 larity. In the case of perfect spheres, one can expect a single value of $\theta = \theta_0$ accord-
 210 ing to Eqn. (1). Therefore, Fig. 4(B) and Fig. 4(C) summarize the important influences
 211 of particle angularity on pore geometry features and contact angle distribution, which
 212 will consequently impact the capillary pressure signal and invasion morphology.

213 3.1 Capillary Pressure Signal

214 As indicated in Fig. 5(A), the evolution of dimensionless capillary pressure P_c^* shows
 215 larger fluctuations for media with squares compared with more spherical grains (dodecagons),
 216 implying greater randomness in local capillary resistance. At the same time, larger mean
 217 value is observed with increasing θ_0 , which is a direct result from greater curvature of
 218 menisci. The distribution of P_{start}^* , the avalanches starting pressure, can also be directly
 219 obtained from the simulation (Fig. 5(B)), where P_{start}^* is the capillary pressure at pressure-
 220 driven event (red circle in Fig. 3(B-i)). For experiments conducted using spherical glass
 221 beads in drainage, P_{start}^* is found to distribute within a relatively narrow region (Måløy
 222 et al., 1992; Furuberg et al., 1996; Moura et al., 2020). The P_{start}^* distribution is linked

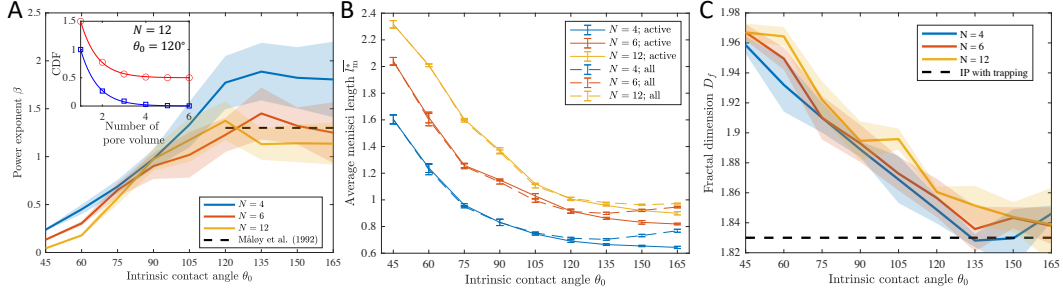


Figure 6. (A) Power exponent β for different grain shapes and wetting conditions. The black-dashed line is from Måløy et al. (Måløy et al., 1992) in drainage experiment with glass beads (since the contact angle is not reported, it is assumed that $\theta_0 > 120^\circ$). Inset: cumulative Haines jump sizes (blue squares) and intervals (red circles) distribution for a typical simulation at $N = 12$ with $\theta_0 = 120^\circ$. The intervals distribution is shifted by 0.5 for visualization purpose. Lines represent exponential fitting with 1.29 and 1.30 for jump sizes and interval sizes, respectively. (B) The normalized average meniscus width \bar{l}_m^* as a function of intrinsic contact angle. Solid (dashed) lines represent values calculated from active (all) menisci. (C) Fractal dimension calculated using box counting method as a function of intrinsic contact angle, with shaded area showing the standard deviation of five simulations.

223 to the total volume capacitance stored in all active menisci (Furuberg et al., 1996), which
 224 reflects the characteristics of pore geometry. For spherical grains with given packing struc-
 225 ture, the capillary resistance is distinct between “pore” and “throat”, leading to the fact
 226 that the avalanches are likely to initialize (and finish) at same location and consequently
 227 similar P_{start}^* . As the shape of particle becomes more angular, the distribution of P_{start}^*
 228 widens as a result of increased impact from random orientations of grains and pinning
 229 of menisci, which is clearly demonstrated in Fig. 5(B). Fig. 5(C) depicts the mean and
 230 standard deviation of P_c^* for all grain shapes and wettability with each value calculated
 231 from five individual simulations. As expected, the average capillary pressure increases
 232 with increasing contact angle, and the fluctuations in capillary pressure are found to be
 233 larger for more angular grains across all wetting conditions. Besides, it can be observed
 234 that \bar{P}_c^* is greater (smaller) for angular grains in drainage (imbibition) conditions, with
 235 a crossover at around $\theta_0 \approx 90^\circ$, which can be attributed to the change in pore and throat
 236 size distribution. It is well understood that the throat (pore) size controls the invasion
 237 process in drainage (imbibition). Fig. 4(C) indicates that greater angularity leads to smaller
 238 average throat size, and in the meantime greater average pore size (as the porosity is the
 239 same), which explains the observed higher capillary pressure in drainage and lower cap-
 240 illary pressure in imbibition.

241 3.2 Haines Jumps and Patterns Characteristics

242 The size of Haines jump can be obtained as the area filled between two pressure-
 243 driven events (shaded area in Fig. 1(D)), where filling events of single and multiple pores
 244 are observed. Both the cumulative pressure jump sizes and intervals distributions dur-
 245 ing drainage experiments have been found to follow an exponential law (Måløy et al.,
 246 1992; Furuberg et al., 1996), which is consistent with the simulation results (inset in Fig. 6A).
 247 The time interval between two jumps is expressed as the injected area of invading fluid,
 248 and the area of invading fluid is expressed in terms of number of average pore volume,
 249 calculated as the total pore space divided by the number of pores. Note that the cumu-
 250 lative intervals distribution is shifted upwards by 0.5 for visualization purpose. The power
 251 exponent β , which is regarded as a signature of the displacement process (Måløy et al.,

1992; Furuberg et al., 1996), is plotted for different grain shapes and wetting conditions (Fig. 6A). It can be seen that β increases with the intrinsic contact angle, reaching a plateau at around $\theta_0 = 120^\circ$. Also, in general, the angularity positively correlates with the power exponent. The power exponent β from Måløy et al. (Måløy et al., 1992) in drainage experiment with glass beads is added as black-dashed line for comparison. Since the contact angle was not reported, it is assumed that $\theta_0 > 120^\circ$. Their value of β is close to the less angular grains (hexagons and dodecagons), which is consistent with the fact that glass beads are comparatively round and smooth.

The average meniscus width \bar{l}_m^* (or the average throat size where menisci are present), normalized by the throat size of porous medium of same porosity filled with mono-dispersed spheres, can reveal the distribution of menisci sizes for different particle shapes and wetting conditions. Fig. 6(B) shows \bar{l}_m^* as a function of intrinsic contact angle for different angularities with or without consideration of menisci belonging to trapped region. For all active menisci (solid lines), \bar{l}_m^* decreases with increasing θ_0 , reflecting stronger stability of pinned meniscus at small throat. Besides, despite constant porosity for all simulations, the average meniscus size is found to be smaller in angular grains as a result of (i) wider distribution of throat sizes (Fig. 4(B)), and (ii) greater capacity of pinning (upper bound in Eqn. (1)) as the local corner becomes sharper, leading to wider distribution of effective contact angles (Fig. 4(C)). If both active and inactive menisci are considered, however, a non-monotonic relationship is observed. This is a result of incompressibility of the trapped ganglia that prevent the menisci from further advancement and ultimately being pinned at narrower throats. Due to increased amount of trapping at larger contact angle (see Fig. 4(A)), this effect becomes significant at extreme non-wetting condition that leads to increase in \bar{l}_m^* . This also implies that the pressure within the trapped ganglia could be lower than the capillary pressure signal measured at the inlet.

To quantify the displacement patterns, the fractal dimension D_f , as a measurement of the degree to which a pattern fills space, is calculated using box counting method. Fig. 6(C) demonstrates the transition from stable displacement with a D_f of around 1.96 towards the regime of capillary fingering with $D_f \approx 1.84$, which is consistent with previously documented values of 1.96 and 1.83 for compact growth and invasion percolation, respectively (Wilkinson & Willemsen, 1983; Lenormand & Zarcone, 1989; Trojer et al., 2015; Zhao et al., 2016; M. J. Blunt, 2017; Primkulov et al., 2018). Furthermore, in spite of considerable variation (standard deviation, represented by the shaded area), an early transition towards capillary fingering, i.e., smaller D_f at the same θ_0 , can be observed for grains with greater angularity, which confirms the qualitative observation in the displacement patterns in Fig.4(A). This could be partially explained by, apart from the variation in local pore structure, the increase of average effective contact angles in angular grains assemblies due to sharp edge pinning effect, which is evident in Fig. 4(C).

In this study, though we considered simplified particle shapes (regular polygons), more general and complex shapes can be easily implemented by changing the coordinates of grain vertices and updating the local corner angles accordingly. Also, it is possible to consider the viscous effect by incorporating, for example, the recently proposed moving capacitor model (Primkulov et al., 2019). Furthermore, in the current work the change in distribution of effective contact angle and throat size have been regarded as a direct result of variation in particle shape (Fig. 4(B) and Fig. 4(C)), as simultaneous variations in these two quantities, under fixed porosity, are inevitable with change in particle shape. It could be interesting to solely look at the impact of menisci pinning phenomena at sharp edges by excluding the change in throat (or pore) size distribution, although this would lead to different overall porosity of samples. Note that, for the choice of particle shapes investigated in this study, square grain is chosen as the most angular case instead of triangle. This is because that with current porosity 0.5912, there will be overlaps of grains, if the shape is triangle, when they are randomly rotated. Since the porosity is already

305 relatively large and we do not want to further increase it, also, we try to avoid manu-
 306 ally specifying extra criterion during media generation and ensure fully random (homo-
 307 geneous and isotropic) porous media, the most angular shape for current grain arrange-
 308 ment and porosity without grain overlap is square. On the other hand, dodecagon is used
 309 to represent circular grain, as the algorithm is not capable of doing perfect circles since
 310 the calculation of critical capillary pressure and advancement of menisci is based on dis-
 311 cretization of the grains, and perfect circles correspond to infinite number of mesh points.
 312 Nevertheless, it was shown that the case for dodecagon is close to circle, as the average
 313 throat size is very close to the porous media filled with perfect circles (Fig. 4(B)).

314 4 Conclusions

315 In conclusion, we presented an extended pore-network model (EPONM) to probe
 316 the effect of grain shapes on quasi-static fluid-fluid displacement in porous media. The
 317 model incorporates the mechanisms of pore-scale instabilities (Cieplak & Robbins, 1988,
 318 1990), volume capacitance model (Måløy et al., 1992; Furuberg et al., 1996), and sharp
 319 edge pinning effect (Gibbs, 1961; Oliver et al., 1977). This allows us to reproduce the
 320 multiphase flow patterns across a wide range of wetting conditions for different grain shapes.
 321 The algorithm, with further extension, i.e., mainly on geometry description and gener-
 322 alization on determination of instability modes, should be applicable to porous media
 323 with arbitrary grain shape/location, such as reconstructed pore geometry from 2D scan
 324 of rocks, offering a rigorous approach for investigation of how topological features mod-
 325 ify the multiphase displacement in porous media.

326 At the pore scale, increase in grain angularity not only introduces greater hetero-
 327 geneity in pore geometry, but also amplify the effect of menisci pinning at corners. This
 328 is directly reflected by the variations in distributions of throat sizes (Fig. 4(B)) and ef-
 329 fective contact angles (Fig. 4(C)), which consequently impact both the mean value and
 330 fluctuation of the capillary pressure signal (Fig. 5(A)). Macroscopically, an earlier tran-
 331 sition from stable displacement towards the regime of capillary fingering is observed both
 332 qualitatively from the invasion morphology (Fig. 4(A)) and quantitatively as indicated
 333 by the fractal dimension (Fig. 6(C)). Various characteristic metrics have been calculated
 334 for comparison with past experimental works, including the distribution of avalanches
 335 starting pressure, Haines jump size and interval. Reasonable agreement is observed, and
 336 impacts of grain shape are discussed. In particular, under the condition of same poro-
 337 sity for all studied cases, the average size of menisci is found to be smaller in porous me-
 338 dia with angular grains, showing a tendency of pinning at narrower throats as a result
 339 of wider distribution of throat sizes (Fig. 4(B)) and greater pinning strength (Eqn. (1)).

340 Our results have provided independent corroboration of wide distribution of con-
 341 tact angles observed experimentally in mineralogically homogeneous porous media. The
 342 profound influences of grain shape are highlighted by systematically analyzing the dis-
 343 placement processes, deepening the understanding of the interplay between pore geom-
 344 etry and wettability. The proposed pore-network model offers an efficient approach for
 345 investigation of multiphase flow in natural porous media.

346 Acknowledgments

347 This work was financially supported by Australian Research Council (Projects DP170102886)
 348 and The University of Sydney SOAR Fellowship. YG acknowledges the financial sup-
 349 port of Labex MMCD(ANR-11-LABX-022-01) for his stay at Laboratoire Navier at ENPC.
 350 ZW thanks Ms Zi Ying for fruitful discussion. Data sets associated with this work are
 351 available online (<https://doi.org/10.6084/m9.figshare.13369733>).

References

- AlRatrou, A., Blunt, M. J., & Bijeljic, B. (2018). Wettability in complex porous materials, the mixed-wet state, and its relationship to surface roughness. *Proceedings of the National Academy of Sciences*, *115*(36), 8901–8906. doi: 10.1073/pnas.1803734115
- Armstrong, R. T., Georgiadis, A., Ott, H., Klemin, D., & Berg, S. (2014). Critical capillary number: Desaturation studied with fast x-ray computed microtomography. *Geophysical Research Letters*, *41*(1), 55–60. doi: 10.1002/2013GL058075
- Blunt, M., Fayers, F., & Orr, F. M. (1993). Carbon dioxide in enhanced oil recovery. *Energy Conversion and Management*, *34*(9), 1197–1204. (Proceedings of the International Energy Agency Carbon Dioxide Disposal Symposium)
- Blunt, M. J. (1998). Physically-based network modeling of multiphase flow in intermediate-wet porous media. *Journal of Petroleum Science and Engineering*, *20*(3), 117–125. doi: [https://doi.org/10.1016/S0920-4105\(98\)00010-2](https://doi.org/10.1016/S0920-4105(98)00010-2)
- Blunt, M. J. (2001). Flow in porous media — pore-network models and multiphase flow. *Current Opinion in Colloid & Interface Science*, *6*(3), 197–207. Retrieved from <http://www.sciencedirect.com/science/article/pii/S135902940100084X> doi: [https://doi.org/10.1016/S1359-0294\(01\)00084-X](https://doi.org/10.1016/S1359-0294(01)00084-X)
- Blunt, M. J. (2017). *Multiphase flow in permeable media: A pore-scale perspective*. Cambridge University Press. doi: 10.1017/9781316145098
- Blunt, M. J., Alhosani, A., Lin, Q., Scanziani, A., & Bijeljic, B. (2021). Determination of contact angles for three-phase flow in porous media using an energy balance. *Journal of Colloid and Interface Science*, *582*, 283–290. doi: <https://doi.org/10.1016/j.jcis.2020.07.152>
- Blunt, M. J., Lin, Q., Akai, T., & Bijeljic, B. (2019). A thermodynamically consistent characterization of wettability in porous media using high-resolution imaging. *Journal of Colloid and Interface Science*, *552*, 59–65. doi: <https://doi.org/10.1016/j.jcis.2019.05.026>
- Cassie, A. B. D., & Baxter, S. (1944). Wettability of porous surfaces. *Trans. Faraday Soc.*, *40*, 546–551. Retrieved from <http://dx.doi.org/10.1039/TF9444000546> doi: 10.1039/TF9444000546
- Chapuis, O., Prat, M., Quintard, M., Chane-Kane, E., Guillot, O., & Mayer, N. (2008). Two-phase flow and evaporation in model fibrous media: Application to the gas diffusion layer of pem fuel cells. *Journal of Power Sources*, *178*(1), 258–268. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0378775307026523> doi: <https://doi.org/10.1016/j.jpowsour.2007.12.011>
- Chen, Y.-F., Wu, D.-S., Fang, S., & Hu, R. (2018). Experimental study on two-phase flow in rough fracture: Phase diagram and localized flow channel. *International Journal of Heat and Mass Transfer*, *122*, 1298–1307. doi: <https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.031>
- Cieplak, M., & Robbins, M. O. (1988, May). Dynamical transition in quasistatic fluid invasion in porous media. *Phys. Rev. Lett.*, *60*, 2042–2045. doi: 10.1103/PhysRevLett.60.2042
- Cieplak, M., & Robbins, M. O. (1990, Jun). Influence of contact angle on quasistatic fluid invasion of porous media. *Phys. Rev. B*, *41*, 11508–11521. doi: 10.1103/PhysRevB.41.11508
- Crisp, D. J., & Thorpe, W. H. (1948). The water-protecting properties of insect hairs. *Discuss. Faraday Soc.*, *3*, 210–220. Retrieved from <http://dx.doi.org/10.1039/DF9480300210> doi: 10.1039/DF9480300210
- Furuberg, L., Måløy, K. J., & Feder, J. (1996, Jan). Intermittent behavior in slow drainage. *Phys. Rev. E*, *53*, 966–977. doi: 10.1103/PhysRevE.53.966
- Gao, N., & Yan, Y. (2009). Modeling superhydrophobic contact angles and wetting transition. *Journal of Bionic Engineering*, *6*(4), 335–340. Retrieved from

- 405 <http://www.sciencedirect.com/science/article/pii/S1672652908601353>
 406 doi: [https://doi.org/10.1016/S1672-6529\(08\)60135-3](https://doi.org/10.1016/S1672-6529(08)60135-3)
- 407 Geistlinger, H., & Zulficar, B. (n.d.). The impact of wettability and surface rough-
 408 ness on fluid displacement and capillary trapping in 2d- and 3d-porous media part
 409 1: Wettability-controlled phase transition of trapping efficiency in glass beads
 410 packs. *Water Resources Research*, *n/a(n/a)*, e2019WR026826. (e2019WR026826
 411 2019WR026826) doi: 10.1029/2019WR026826
- 412 Gibbs, J. W. (1961). *The scientific papers* (Vol. 1). New York: Dover Publications.
- 413 Holtzman, R. (2016). Effects of pore-scale disorder on fluid displacement in
 414 partially-wettable porous media [Journal Article]. *Sci Rep*, *6*, 36221. doi:
 415 10.1038/srep36221
- 416 Holtzman, R., & Segre, E. (2015, Oct). Wettability stabilizes fluid invasion into
 417 porous media via nonlocal, cooperative pore filling. *Phys. Rev. Lett.*, *115*, 164501.
 418 doi: 10.1103/PhysRevLett.115.164501
- 419 Hu, R., Lan, T., Wei, G.-J., & Chen, Y.-F. (2019). Phase diagram of quasi-static
 420 immiscible displacement in disordered porous media. *Journal of Fluid Mechanics*,
 421 *875*, 448–475. doi: 10.1017/jfm.2019.504
- 422 Ju, Y., Gong, W., Chang, W., & Sun, M. (2020). Effects of pore character-
 423 istics on water-oil two-phase displacement in non-homogeneous pore struc-
 424 tures: A pore-scale lattice boltzmann model considering various fluid den-
 425 sity ratios. *International Journal of Engineering Science*, *154*, 103343. doi:
 426 <https://doi.org/10.1016/j.ijengsci.2020.103343>
- 427 Jung, M., Brinkmann, M., Seemann, R., Hiller, T., Sanchez de La Lama, M., &
 428 Herminghaus, S. (2016, Nov). Wettability controls slow immiscible displace-
 429 ment through local interfacial instabilities. *Phys. Rev. Fluids*, *1*, 074202. doi:
 430 10.1103/PhysRevFluids.1.074202
- 431 Lake, L. W., Johns, R., Rossen, B., & Pope, G. (2014). *Fundamentals of enhanced*
 432 *oil recovery*. Society of Petroleum Engineers.
- 433 Lenormand, R. (1990, dec). Liquids in porous media. *Journal of Physics: Con-*
 434 *densed Matter*, *2*(S), SA79–SA88. Retrieved from [https://doi.org/10.1088/](https://doi.org/10.1088/0953-8984/2/s/008)
 435 [0953-8984/2/s/008](https://doi.org/10.1088/0953-8984/2/s/008) doi: 10.1088/0953-8984/2/s/008
- 436 Lenormand, R., Touboul, E., & Zarcone, C. (1988). Numerical models and exper-
 437 iments on immiscible displacements in porous media [Journal Article]. *Journal of*
 438 *Fluid Mechanics*, *189*(165-187). doi: 10.1017/s0022112088000953
- 439 Lenormand, R., & Zarcone, C. (1989, Dec 01). Capillary fingering: Percolation
 440 and fractal dimension. *Transport in Porous Media*, *4*(6), 599–612. doi: 10.1007/
 441 BF00223630
- 442 Lipiec, J., Kuś, J., Słowińska-Jurkiewicz, A., & Nosalewicz, A. (2006). Soil porosity
 443 and water infiltration as influenced by tillage methods. *Soil and Tillage Research*,
 444 *89*(2), 210 - 220. doi: <https://doi.org/10.1016/j.still.2005.07.012>
- 445 Måløy, K. J., Furuberg, L., Feder, J., & Jøssang, T. (1992, Apr). Dynamics of
 446 slow drainage in porous media. *Phys. Rev. Lett.*, *68*, 2161–2164. Retrieved
 447 from <https://link.aps.org/doi/10.1103/PhysRevLett.68.2161> doi:
 448 10.1103/PhysRevLett.68.2161
- 449 Marmur, A. (2003). Wetting on hydrophobic rough surfaces: To be heterogeneous
 450 or not to be? *Langmuir*, *19*(20), 8343-8348. Retrieved from [https://doi.org/10](https://doi.org/10.1021/la0344682)
 451 [.1021/la0344682](https://doi.org/10.1021/la0344682) doi: 10.1021/la0344682
- 452 Mason, G., & Morrow, N. R. (1994). Effect of contact angle on capillary displace-
 453 ment curvatures in pore throats formed by spheres. *Journal of Colloid and Inter-*
 454 *face Science*, *168*(1), 130-141. Retrieved from [https://www.sciencedirect.com/](https://www.sciencedirect.com/science/article/pii/S0021979784714020)
 455 [science/article/pii/S0021979784714020](https://www.sciencedirect.com/science/article/pii/S0021979784714020) doi: [https://doi.org/10.1006/](https://doi.org/10.1006/jcis.1994.1402)
 456 [jcis.1994.1402](https://doi.org/10.1006/jcis.1994.1402)
- 457 Matter, J. M., Stute, M., Snæbjörnsdóttir, S. Ó., Oelkers, E. H., Gislason, S. R.,
 458 Aradóttir, E. S., ... Broecker, W. S. (2016). Rapid carbon mineralization for per-

- 459 manent disposal of anthropogenic carbon dioxide emissions. *Science*, *352*(6291),
460 1312–1314. doi: 10.1126/science.aad8132
- 461 Mehmani, A., Kelly, S., Torres-Verdín, C., & Balhoff, M. (2019). Residual
462 oil saturation following gas injection in sandstones: Microfluidic quantifica-
463 tion of the impact of pore-scale surface roughness. *Fuel*, *251*, 147 - 161. doi:
464 <https://doi.org/10.1016/j.fuel.2019.02.118>
- 465 Mishra, H., Schrader, A. M., Lee, D. W., Gallo, A., Chen, S.-Y., Kaufman, Y., ...
466 Israelachvili, J. N. (2016). Time-dependent wetting behavior of pdms surfaces
467 with bioinspired, hierarchical structures. *ACS Applied Materials & Interfaces*,
468 *8*(12), 8168-8174. Retrieved from <https://doi.org/10.1021/acsami.5b10721>
469 doi: 10.1021/acsami.5b10721
- 470 Moulinet, S., & Bartolo, D. (2007, Nov 01). Life and death of a fakir droplet: Im-
471 plement transitions on superhydrophobic surfaces. *The European Physical Jour-
472 nal E*, *24*(3), 251–260. Retrieved from [https://doi.org/10.1140/epje/i2007-
473 -10235-y](https://doi.org/10.1140/epje/i2007-10235-y) doi: 10.1140/epje/i2007-10235-y
- 474 Moura, M., Måløy, K. J., Flekkøy, E. G., & Toussaint, R. (2020). Intermittent
475 dynamics of slow drainage experiments in porous media: Characterization un-
476 der different boundary conditions. *Frontiers in Physics*, *7*, 217. Retrieved from
477 <https://www.frontiersin.org/article/10.3389/fphy.2019.00217> doi:
478 10.3389/fphy.2019.00217
- 479 Nadim, F., Hoag, G. E., Liu, S., Carley, R. J., & Zack, P. (2000). Detection and
480 remediation of soil and aquifer systems contaminated with petroleum products: an
481 overview. *Journal of Petroleum Science and Engineering*, *26*(1), 169 - 178.
- 482 Oliver, J., Huh, C., & Mason, S. (1977). Resistance to spreading of liquids by sharp
483 edges. *Journal of Colloid and Interface Science*, *59*(3), 568 - 581. Retrieved from
484 <http://www.sciencedirect.com/science/article/pii/0021979777900522>
485 doi: [https://doi.org/10.1016/0021-9797\(77\)90052-2](https://doi.org/10.1016/0021-9797(77)90052-2)
- 486 Papadopoulos, P., Mammen, L., Deng, X., Vollmer, D., & Butt, H.-J. (2013). How
487 superhydrophobicity breaks down. *Proceedings of the National Academy of Sci-
488 ences*, *110*(9), 3254–3258. Retrieved from [https://www.pnas.org/content/110/
489 9/3254](https://www.pnas.org/content/110/9/3254) doi: 10.1073/pnas.1218673110
- 490 Prinkulov, B. K., Pahlavan, A. A., Fu, X., Zhao, B., MacMinn, C. W., & Juanes,
491 R. (2019). Signatures of fluid–fluid displacement in porous media: wetta-
492 bility, patterns and pressures. *Journal of Fluid Mechanics*, *875*, R4. doi:
493 10.1017/jfm.2019.554
- 494 Prinkulov, B. K., Talman, S., Khaleghi, K., Rangriz Shokri, A., Chalaturnyk, R.,
495 Zhao, B., ... Juanes, R. (2018, Oct). Quasistatic fluid-fluid displacement in
496 porous media: Invasion-percolation through a wetting transition. *Phys. Rev.
497 Fluids*, *3*, 104001. doi: 10.1103/PhysRevFluids.3.104001
- 498 Purcell, W. (1950, 08). Interpretation of Capillary Pressure Data. *Journal of
499 Petroleum Technology*, *2*(08), 11-12. Retrieved from [https://doi.org/10.2118/
500 950369-G](https://doi.org/10.2118/950369-G) doi: 10.2118/950369-G
- 501 Rabbani, H. S., Or, D., Liu, Y., Lai, C.-Y., Lu, N. B., Datta, S. S., ... Shokri,
502 N. (2018). Suppressing viscous fingering in structured porous media. *Pro-
503 ceedings of the National Academy of Sciences*, *115*, 4833-4838. doi: 10.1073/
504 pnas.1800729115
- 505 Ran, H., Jiamin, W., Zhibing, Y., Yi-Feng, C., & Tetsu, T. (2018). Wettability
506 and flow rate impacts on immiscible displacement: A theoretical model. *Geophysi-
507 cal Research Letters*, *45*(7), 3077-3086. doi: 10.1002/2017GL076600
- 508 Sbragaglia, M., Peters, A. M., Pirat, C., Borkent, B. M., Lammertink, R. G. H.,
509 Wessling, M., & Lohse, D. (2007, Oct). Spontaneous breakdown of super-
510 hydrophobicity. *Phys. Rev. Lett.*, *99*, 156001. Retrieved from [https://
511 link.aps.org/doi/10.1103/PhysRevLett.99.156001](https://link.aps.org/doi/10.1103/PhysRevLett.99.156001) doi: 10.1103/
512 PhysRevLett.99.156001

- 513 Seo, D., Schrader, A. M., Chen, S.-Y., Kaufman, Y., Cristiani, T. R., Page, S. H.,
 514 ... Israelachvili, J. N. (2018). Rates of cavity filling by liquids. *Proceed-*
 515 *ings of the National Academy of Sciences*, *115*(32), 8070–8075. Retrieved from
 516 <https://www.pnas.org/content/115/32/8070> doi: 10.1073/pnas.1804437115
- 517 Szulczewski, M. L., MacMinn, C. W., Herzog, H. J., & Juanes, R. (2012). Lifetime
 518 of carbon capture and storage as a climate-change mitigation technology. *Proceed-*
 519 *ings of the National Academy of Sciences*, *109*(14), 5185–5189. doi: 10.1073/pnas
 520 .1115347109
- 521 Trojer, M., Szulczewski, M. L., & Juanes, R. (2015, May). Stabilizing fluid-fluid dis-
 522 placements in porous media through wettability alteration. *Phys. Rev. Applied*, *3*,
 523 054008. doi: 10.1103/PhysRevApplied.3.054008
- 524 Wang, Z., Chauhan, K., Pereira, J.-M., & Gan, Y. (2019, Mar). Disorder character-
 525 ization of porous media and its effect on fluid displacement. *Phys. Rev. Fluids*, *4*,
 526 034305. doi: 10.1103/PhysRevFluids.4.034305
- 527 Wang, Z., Pereira, J.-M., & Gan, Y. (2020). Effect of wetting transition during
 528 multiphase displacement in porous media. *Langmuir*, *36*(9), 2449–2458. (PMID:
 529 32070092) doi: 10.1021/acs.langmuir.9b03780
- 530 Wenzel, R. N. (1936). Resistance of solid surfaces to wetting by water. *Indus-*
 531 *trial & Engineering Chemistry*, *28*(8), 988–994. Retrieved from [https://doi.org/](https://doi.org/10.1021/ie50320a024)
 532 [10.1021/ie50320a024](https://doi.org/10.1021/ie50320a024) doi: 10.1021/ie50320a024
- 533 Wilkinson, D., & Willemsen, J. F. (1983, oct). Invasion percolation: a new form
 534 of percolation theory. *Journal of Physics A: Mathematical and General*, *16*(14),
 535 3365–3376. Retrieved from <https://doi.org/10.1088/0305-4470/16/14/028>
 536 doi: 10.1088/0305-4470/16/14/028
- 537 Xu, W., Ok, J. T., Xiao, F., Neeves, K. B., & Yin, X. (2014). Effect of pore ge-
 538 ometry and interfacial tension on water-oil displacement efficiency in oil-wet
 539 microfluidic porous media analogs. *Physics of Fluids*, *26*(9), 093102. doi:
 540 10.1063/1.4894071
- 541 Yortsos, Y. C., Xu, B., & Salin, D. (1997, Dec). Phase diagram of fully de-
 542 veloped drainage in porous media. *Phys. Rev. Lett.*, *79*, 4581–4584. doi:
 543 10.1103/PhysRevLett.79.4581
- 544 Zhao, B., MacMinn, C. W., & Juanes, R. (2016). Wettability control on multiphase
 545 flow in patterned microfluidics. *Proceedings of the National Academy of Sciences*,
 546 *113*(37), 10251–10256. doi: 10.1073/pnas.1603387113
- 547 Zulfiqar, B., Vogel, H., Ding, Y., Golmohammadi, S., K uchler, M., Reuter, D.,
 548 & Geistlinger, H. (n.d.). The impact of wettability and surface roughness on
 549 fluid displacement and capillary trapping in 2d- and 3d-porous media: Part
 550 2: Combined effect of wettability, surface roughness, and pore space structure
 551 on trapping efficiency in sand packs and micromodels. *Water Resources Re-*
 552 *search*, *n/a*(n/a), e2020WR027965. (e2020WR027965 2020WR027965) doi:
 553 10.1029/2020WR027965