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## Trapping and escape of viscous fingers in a soft Hele-Shaw cell

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Viscous flow in the narrow gap between a rigid plate and a confined elastic solid has been observed to “choke” at high flow rates, due to the deforming solid making contact with the plate and sealing the gap. When the viscous flow is driven by injection of a gas bubble, the advancing meniscus is susceptible to the viscous-fingering instability. By comparing fingering experiments with axisymmetric numerical simulations, we demonstrate that, depending on the width of the fingers, the fingering instability can either promote or suppress choking, i.e., cause the system to choke when an axisymmetric system would not, or vice versa.

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Interactions between interfacial flows and deformable components are encountered frequently in industry and technology. Traditionally, soft components are introduced to systems as a secondary means of modifying interfacial instabilities to our advantage. For example, the Rayleigh-Taylor instability is amplified in solidifying melts to produce soft solids with complex surface geometry [1], while the onset of the ribbing instability during roll coating is suppressed towards larger roll speeds if the rolls are covered by a compliant material [2,3]. More recently, soft components have also become primary in the design of advanced technologies, including nanoscale assembly [4], wearable sensing devices [5,6], and soft robotics [7], where two-phase flows are exploited for fabrication and actuation. A fundamental understanding of the potential interactions between multiphase flows and deformable components is therefore essential, and yet only a handful of model systems have so far been examined.

One such model system with relevance to both soft technological components and interfacial instabilities is a deformable Hele-Shaw cell. A rigid Hele-Shaw cell comprises a narrow gap between two parallel plates. The viscous-fingering instability, which occurs when a gas displaces a viscous liquid between the plates, has been studied extensively as a canonical interfacial instability with relevance to enhanced oil recovery [8] and carbon sequestration [9]. This instability was previously coupled to deformable components by replacing one of the rigid plates with an elastic membrane, creating an *unconfined* soft Hele-Shaw cell, which delayed the onset of the instability [10]. Here, we study a *confined* soft Hele-Shaw cell in which the deformable wall is a volumetrically confined slab of elastomer [see Fig. 1(a)]. A recent study showed that, for steady single-phase injection, a confined soft flow cell behaves as a liquid fuse with possible applications to microfluidics and soft

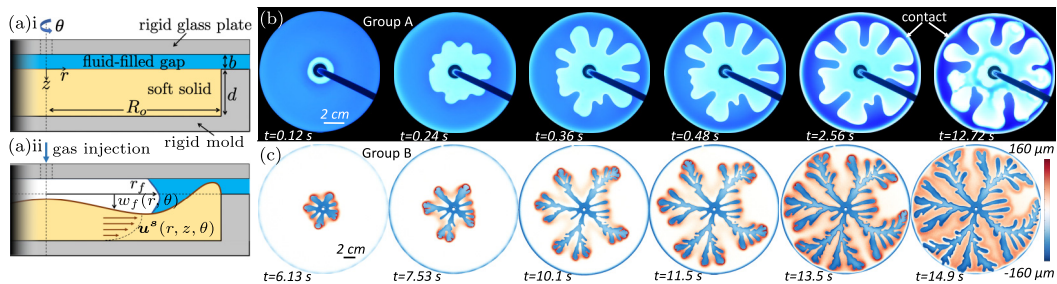


FIG. 1. (a) Schematic of the setup (a)i before and (a)ii after the start of gas injection. Here,  $r_f(\theta)$  is the radial extent of the interface,  $\mathbf{u}^s(r, \theta, z)$  is the solid displacement vector, and  $w_f(r, \theta) = u_z^s(r, \theta, 0)$ . (b), (c) Top view of an injected gas bubble displacing viscous liquid in the narrow gap between a glass plate and a confined slab of elastomer. Images taken at different times  $t$  after gas injection started. (b) Group A: The liquid is dyed blue, so darker color indicates a thicker layer of liquid. Flow-induced deformation of the elastomer eventually leads to contact between the soft slab and the glass plate in the vicinity of the cell rim (visible as a white band encircling the cell), trapping the viscous fingers within the cell. ( $R_o = 60$  mm,  $d = 7$  mm,  $b = 1.5$  mm,  $G = 1.15$  kPa,  $\mu = 0.8$  Pa s,  $\gamma = 63$  mN/m,  $Q_0 = 500$  ml/min.) (The slow dewetting of the film in the bubble region visible in the last panel did not affect the growth of the fingering instability.) (c) Group B: The coloring shows change in liquid-layer thickness relative to the thickness of the initial gap  $b$ , with red and blue shades outside the bubble region corresponding to expansion and contraction of the gap, respectively (see color bar). The fingers escape the cell despite constriction near the rim. ( $R_o = 95$  mm,  $d = 4$  mm,  $b = 0.16$  mm,  $G = 4.2$  kPa,  $\mu = 1.02$  Pa s,  $\gamma = 63$  mN/m,  $Q_0 = 49.4$  ml/min.)

robotics [11]; mechanically, the elastomer is sheared outwards with the flow and accumulates in a boundary layer near the outlet, which constricts the flow and, above a critical flow rate, “chokes” the flow entirely. We now extend these previous studies by considering two-phase flow in a confined soft flow cell and investigate whether the cell still chokes at a critical flux, and the role of viscous fingering in this process.

Figures 1(b) and 1(c) show two experiments where an injected bubble develops fingers that either become trapped in the choked cell [Fig. 1(b)] or escape the cell, which in turn fails to choke [Fig. 1(c)]. Surprisingly, numerical simulations of axisymmetric bubble expansion in a confined soft flow cell for the same flow rates show the opposite behavior, choking for the parameters of Fig. 1(c), but not those of Fig. 1(b). This difference in choking behavior must be due to the viscous fingering, as the simulations are in quantitative agreement with experiments in cases when fingering is negligible and the interface is nearly circular. Using this comparison between experiments and axisymmetric mathematical modeling, we elucidate the fluid-structure interactions that enable both the trapping and escape of viscous fingers and thus demonstrate a systematic relationship between the outcome and interface morphology.

Two groups of experiments, labeled group A and group B, were performed by the Manchester and Oxford groups, respectively, using radially outward injection into confined soft Hele-Shaw cells [Fig. 1(a)]. Silicone-based elastomer was cured in cylindrical molds of radius  $R_o$  and depth  $d$  to create nearly incompressible soft slabs with aspect ratio  $\mathcal{A}_s = R_o/d$ , which remained adhered to, and confined by, the mold. The initial separation distance  $b$  between the soft substrate and the overlying glass plate (and the corresponding gap aspect ratio  $\mathcal{A}_f = R_o/b$ ) was set by spacers. The flow cell was prefilled with glycerol, and gas was injected into the prefilled cell through a port in the center of the glass plate at nominal volumetric flow rate  $Q_0$ . The properties of the elastomer (shear modulus  $G$  and Poisson’s ratio  $\nu$ ) and glycerol (viscosity  $\mu$  and surface tension  $\gamma$ ) were either measured prior to each experiment or inferred from published data. The evolution of the interface was captured by a camera from above. For group B, the deflection of the whole substrate ahead of the interface was quantified using a custom-built light-attenuation technique (see Supplemental Material [12]).

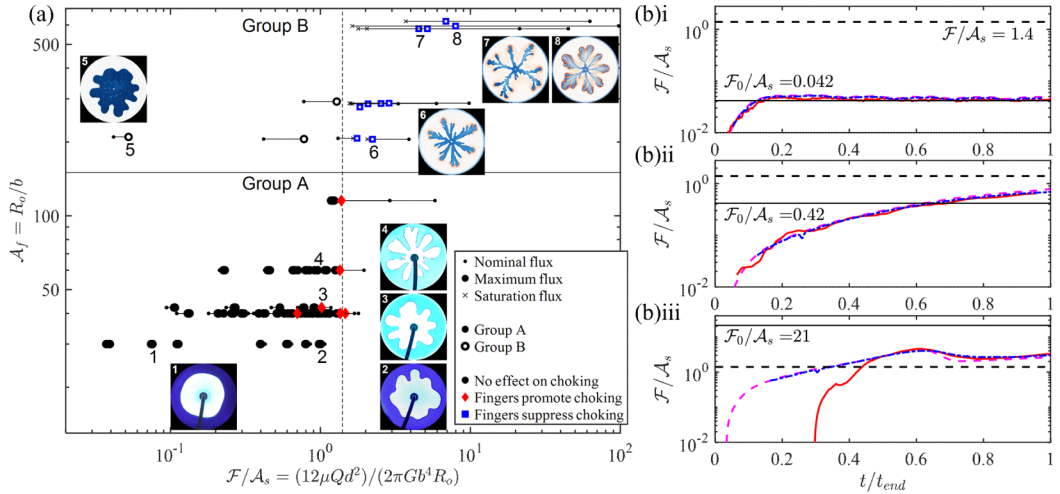


FIG. 2. (a) Phase diagram of experimental results in different soft Hele-Shaw cells in terms of gap aspect ratio  $\mathcal{A}_f = R_o/b$  vs nondimensional flow rate  $\mathcal{F}/\mathcal{A}_s$  [12]. The quantity  $\mathcal{F}/\mathcal{A}_s$  is calculated using both the maximal value of the flow rate  $Q(t)$  observed experimentally for  $r_f < R_o - d$  (large markers) and the nominal imposed injection flow rate  $Q_0$  (small dots), connected by a horizontal line. The critical value of  $\mathcal{F}/\mathcal{A}_s \approx 1.4$ , above which the cells would choke for single-phase flow [11], is shown with the vertical dashed line. Marker shapes and colors indicate whether choking occurred in the experiments or in analogous axisymmetric simulations following the experimentally measured  $Q(t)$ . (In no case did choking occur in both.) A representative selection of instantaneous interface shapes and the corresponding points in the phase diagram are marked with numbers 1 to 8. (b) Typical evolution of the nondimensional flow rate  $\mathcal{F}/\mathcal{A}_s$ , with time  $t$ , normalized by the duration of the experiment  $t_{\text{end}}$ , for when (i)  $\mathcal{F}/\mathcal{A}_s$  settles to the nominal (imposed) value  $\mathcal{F}_0/\mathcal{A}_s$  (solid horizontal lines), (ii)  $\mathcal{F}/\mathcal{A}_s$  continues growing throughout the experiment, and (iii)  $\mathcal{F}/\mathcal{A}_s$  grows before saturating at a value close to the single-phase choking threshold  $\mathcal{F}/\mathcal{A}_s \approx 1.4$  (dashed horizontal lines). The saturation flow rate (i.e., the minimum obtained after the peak) is plotted in panel (a) as crosses connected by horizontal lines for the relevant experiments in group B. The data correspond to the experiments done with  $R_o = 95$  mm,  $d = 4$  mm,  $\gamma = 63$  mN/m: (i)  $G = 2.9$  kPa,  $Q_0 = 1$  ml/min,  $b = 0.45$  mm,  $\mu = 0.95$  Pa s; (ii)  $G = 2.9$  kPa,  $Q_0 = 10$  ml/min,  $b = 0.46$  mm,  $\mu = 1.03$  Pa s; and (iii)  $G = 3.9$  kPa,  $Q_0 = 11.1$  ml/min,  $b = 0.16$  mm,  $\mu = 1.01$  Pa s. The time evolution was obtained by time differentiating the volume of fluid in the cell as measured by light attenuation (blue dash-dotted line, group B only), measuring the gas pressure to infer the gas volume (red solid line, various experiments), and inferring the volume of liquid displaced by the advancing meniscus using a traveling-wave model (magenta dashed line, all experiments). The three methods agree, and we therefore choose to report traveling-wave-based measurements in panel (a) [12].

Figure 2(a) summarizes results from more than 150 experiments. The vertical axis is the gap aspect ratio  $\mathcal{A}_f = R_o/b$ , while the horizontal axis is the nondimensional quantity  $\mathcal{F}/\mathcal{A}_s = 12\mu Qd^2/(2\pi Gb^4R_o)$ , which can be interpreted as a nondimensional flow rate. Insets of Fig. 2(a) illustrate the range of interface morphologies observed due to viscous fingering. In a rigid cell, fingering would be controlled by two nondimensional parameters:  $\mathcal{A}_f$  and the capillary number  $\text{Ca} = \mu Q/(2\pi R_o b \gamma)$  (note that Ca is proportional to  $\mathcal{F}/\mathcal{A}_s$  by a constant factor  $12d^2\gamma/(Gb^3)$  for any given experiment). References [13–15] predict larger growth rates and wave numbers when  $\mathcal{A}_f$  and/or Ca increase. Consistent with these expectations, we see more branching and narrower fingers as  $\mathcal{A}_f$  and/or  $\mathcal{F}/\mathcal{A}_s$  increase [i.e., moving upward and/or to the right in Fig. 2(a)]. For example, compare experiments in the lower left (e.g., inset 1) where the interface remains almost circular to those in the upper right (insets 6–8) where the interface develops long and narrow or highly branched and fractal fingers. Morphologies intermediate to these extremes are shown by insets 2, 3, and 4, obtained at approximately the same  $\mathcal{F}/\mathcal{A}_s$  and Ca but increasing  $\mathcal{A}_f$ . Hence, traditional rigid-cell

control parameters appear to qualitatively describe the fingering pattern. Notably absent from these results is any evidence that deformation significantly suppresses the instability, as it has been shown to do in unconfined soft flow cells (see Ref. [10]). A prominent feature of our results, absent from both rigid and unconfined soft flow cells, is that the fingers can become trapped by choking around the rim. As discussed above, choking is a key feature of single-phase flow in confined soft flow cells. We next assess the extent to which fingering can promote or suppress this choking phenomenon.

For steady single-phase injection, our cells would choke for flow rates above the critical value

$$\mathcal{F}/\mathcal{A}_s \approx 1.4, \quad (1)$$

marked with a vertical dashed line in Fig. 2(a) [11]. This simple picture is not borne out in our system, where in several experiments the flow rate greatly exceeded the threshold without choking [blue squares in Fig. 2(a)], while in experiments that did choke (red diamonds) choking often occurred below the threshold. There are three key differences between our experiments and steady single-phase injection.

(i) The actual injection rate, i.e., the rate of change of gas volume in the cell, varies in time due to the effects of gas compression.

(ii) The pressure drop required to drive the flow decreases with time as gas displaces liquid.

(iii) Viscous fingering generates a nonaxisymmetric interface and flow field.

Before we can assess the impact of fingering [point (iii)], we must understand the effects of points (i) and (ii).

Each experiment is plotted as a small dot in Fig. 2(a), indicating its nominal nondimensional flow rate  $\mathcal{F}_0/\mathcal{A}_s = 12\mu Q_0 d^2 / (2\pi G b^4 R_o)$ , connected by a horizontal line to a large marker, indicating the maximal flow rate  $Q(t)$  observed in the experiment. We measured  $Q(t)$  in the experiments using three different methods, all of which agreed [see Fig. 2(b) and Supplemental Material [12]]. The time evolution of  $Q(t)$  is caused by gas compression, and is significant for small gap  $b$  or large nominal flow rate  $Q_0$ . Specifically,  $Q(t)$  is delayed in reaching  $Q_0$  while gas in the bubble is compressed, which pressurizes the bubble and drives flow [see Fig. 2(b)]. The gas eventually depressurizes as the interface advances and the viscous resistance decreases, leading to an overshoot of the flow rate followed by slow decay towards  $Q_0$  [Fig. 2(b)i], although the experiment may end while still in the pressurization phase due to a finger escaping [Fig. 2(b)ii]. For large  $Q_0$  (i.e.,  $\mathcal{F}_0/\mathcal{A}_s \gg 1.4$ ), a near-choking state can be obtained, in which a balance between gas compression and constriction near the rim prevents  $Q$  from rising above the critical value for single-phase choking given by Eq. (1), although the choking threshold may be transiently exceeded before the constriction is established [Fig. 2(b)iii]. The near-choking state explains the blue points in Fig. 2(a) with maximal  $Q(t)$  above the choking threshold. In this regime only, we also use a third marker in Fig. 2(a) (crosses) to show near-choking flow rates [i.e., the minimal measurement after the peak in  $Q(t)$ ], which lie close to the threshold and are well below the nominal flow rate.

To assess the effects of two-phase flow and air compression in the absence of fingering, we use numerical simulations of axisymmetric two-phase displacement in a soft Hele-Shaw cell. The equations of linear elasticity for the elastomer in the domain  $0 < r < R_o$ ,  $0 < z < d$ ,

$$\nabla \cdot \mathbf{u}^s + \frac{3(1-2\nu)}{2(1+\nu)} \frac{p^s}{G} = 0, \quad (2a)$$

$$\nabla \cdot \boldsymbol{\sigma}^s = -\frac{3}{2(1+\nu)} \nabla p^s + G \nabla^2 \mathbf{u}^s = \mathbf{0}, \quad (2b)$$

where  $\mathbf{u}^s$  is the displacement vector,  $\boldsymbol{\sigma}^s$  is the stress tensor, and  $p^s = -\text{Tr}(\boldsymbol{\sigma}^s)/3$  is the solid pressure, were coupled to the depth-averaged lubrication equations for viscous incompressible flow of liquid ( $\mathcal{A}_f = R_o/b \gg 1$ ) in the region  $r_f < r < R_o$ ,

$$\frac{\partial w_f}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{(b+w_f)^3}{12\mu} \frac{\partial p}{\partial r} \right), \quad (3)$$

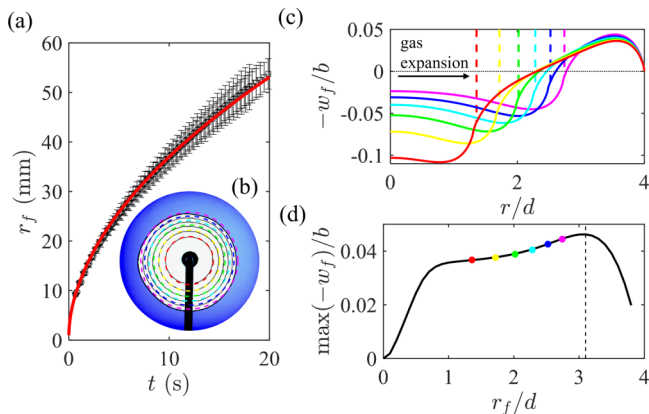


FIG. 3. Direct comparison between experiments and numerics for  $R_o = 60$  mm,  $d = 15$  mm,  $b = 2$  mm,  $G = 1.36$  kPa,  $\mu = 0.72$  Pa s,  $\gamma = 63$  mN/m, and  $Q_0 = 50$  ml/min, when the interface remains circular. (a) Time evolution of the interface radius  $r_f$  obtained numerically (solid line) and in three separate experimental runs (markers showing average with error bars showing standard deviation). (b) A superposition of instantaneous interfacial shapes obtained experimentally (solid lines) and numerically (dashed lines), with spacing  $\Delta t = 1.82$  s starting from  $t = 3.26$  s after the start of the injection. (c) Numerically obtained radial profiles of the deflection of the solid free surface scaled by the initial gap thickness,  $-w_f/b$ , as a function of radial position normalized by the solid thickness,  $r/d$ , and the corresponding instantaneous positions of the interface (vertical dashed lines, see also dots in (d)), at the same times as in panel (b). (d) The evolution of the height of the bulge scaled by the initial gap thickness,  $\max(-w_f)/b$ , as a function of the interface position normalized by the solid thickness,  $r_f/d$ . The dashed line indicates the interface position, for which the bulge height starts decreasing. Note that in panels (c) and (d) the rim is at  $r/d = r_f/d = 4$ .

where  $w_f(r, t)$  is the vertical deformation of the cell and  $p(r, t)$  is the fluid pressure, while assuming a spatially uniform pressure inside the expanding circular gas bubble with the interface at  $r = r_f$ . The coupling between the fluid and the elastic substrate was imposed at  $z = 0$ , by matching  $w_f$  and  $p$  from the lubrication problem with the  $z$  components of  $\mathbf{u}^s$  and  $\sigma^s$  from the solid problem, while the shear stress from the fluid onto the solid was neglected. The elasticity equations were subjected to the no-slip boundary conditions on the mold and symmetry conditions at the cell center. At the displacement front  $r = r_f(t)$ , the kinematic and dynamic boundary conditions were modified to account for residual liquid films [16], and the volumetric flow rate and pressure were imposed at the cell rim [12].

The evolution of the gap constriction at the rim depends on the time evolution of the flow rate  $Q(t)$ . Even in an axisymmetric system, the flow rate would deviate from its nominal value of  $Q_0$  due to compressibility; fingering contributes to this deviation by modifying the effective viscous resistance. To directly compare a fingering flow with an axisymmetric flow in terms of the resulting impact on choking, we therefore impose the experimentally measured  $Q(t)$  in the numerics.

The effects of axisymmetric two-phase flow on the elastomer deformation are illustrated by comparing numerical simulations with an experiment in which the interface remained nearly circular. In this regime, we observe strong quantitative agreement for the time-evolving radius and shape of the interface [Figs. 3(a) and 3(b)]. Numerically, we find that the gradient in pressure that drives the liquid outward also shears the soft slab toward the confining rim [Fig. 3(c)]. This generates the constriction (i.e., the minimum gap) close to the cell rim where sheared material accumulates in a boundary layer [11]. Inside the bubble, the spatially uniform pressure has no shearing effect on the incompressible solid, which consequently relaxes back toward its undeformed state. Near the interface, the cell gap attains its maximum, due to the solid being sheared away from it on the liquid side only. Since the soft solid is adhered to the plate mold, stresses applied to the solid surface only



affect an  $O(d)$  region around the point of application, and so the effects of the interface only reach an  $O(d)$  length into the liquid region. As the interface approaches within  $O(d)$  of the rim, the volume of material sheared toward the rim diminishes and the constriction reduces in size [Fig. 3(d)]. Hence, two-phase flow without fingering acts to suppress choking due to the interaction between the interface and the rim at a distance  $O(d)$ , which we refer to as the “proximity mechanism.” Viscous fingering should enhance this effect because the complex interface extends closer to the rim than a circular bubble growing at the same rate (see Fig. S1 in Supplemental Material [12]). Indeed, comparing analogous simulations with the high-flow rate experiments in group B [blue squares in Fig. 2(a)], we find that choking is predicted in axisymmetric simulations, yet it is absent in the experiments.

Conversely, we also find evidence that fingering can promote choking, compared with axisymmetric two-phase displacement. Specifically, for the experiments in group A in which choking was observed [red diamonds in Fig. 2(a)], simulations did not choke for the same flow rate  $Q(t)$ . In the experiments, the nonaxisymmetric flow field generated by the instability increases the local flow ahead of the advancing fingers [relative to the uniformly distributed flow rate  $Q/(2\pi R_o)$  in the case of an axisymmetric interface], which can promote localized choking near the rim ahead of the fingers even when the azimuthally averaged flux is below the choking threshold. Once choking occurs locally, the flux increases in all nonchoked regions and the obstruction rapidly spreads around the entire flow cell. The nonaxisymmetry in the flow field decays ahead of the fingers on a length scale comparable to the finger width, so this “focusing mechanism” allows wider fingers to promote choking from a further distance.

Whether fingering promotes or suppresses choking depends on which mechanism is dominant, which itself depends on finger morphology. When the interface is far away from the rim, neither mechanism has an effect. As the interface comes closer, for wider fingers the focusing mechanism has a further reach, so it becomes dominant first and may trigger choking before the bulge is affected enough by the proximity mechanism; for narrower fingers, the reverse is true. At large  $\mathcal{A}_f$ , associated with branched and narrow fingers [blue squares in Fig. 2(a)], choking is therefore heavily suppressed even for flow rates beyond the axisymmetric choking threshold. (Additionally, for high flow rates and narrow gaps, the small compressibility of the solid may start to play a role and would also reduce bulging [17].) For experiments with lower  $\mathcal{A}_f$  associated with moderate, relatively wide fingering [red diamonds in Fig. 2(a)], the focusing mechanism is dominant and choking is promoted. Note that in the majority of the parameter space examined neither the experiments nor the simulations choked [black circles in Fig. 2(a)].

In our study of two-phase flow in a confined soft Hele-Shaw cell, we found no evidence that viscous fingering is significantly suppressed as it is in an unconfined soft flow cell [10]. Moreover, the well-defined choking behavior observed for single-phase flow [11] may be either suppressed or promoted by the presence of the instability, compared with an analogous axisymmetric system. Thus, the system studied here exhibits neither of the core characteristics of its parent systems. It is also quite distinct from elastic fingering [18] and fingering in viscoelastic fluids [19]. Similar richness of behavior to that observed here can be expected in related multiphase flows interacting with soft components, for example, in soft microfluidics [20] and deformable porous media [21]. We are currently developing more detailed quantitative predictions of fingering and complex fluid-structure interaction near the cell rim in confined soft Hele-Shaw cells, which could directly benefit such practical applications.

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