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ABSTRACT

We study the dynamics of microfluidic fronts driven by pulsatile pressures in the presence of patches of hydrophilic wetting on the walls of the confining media. To do so, we use a recently developed phase-field model that takes inertia into account. We track the interface position in channels with different spacing between the patches and observe that the smaller the spacing, the faster the advancement of the front. We find that the wetting patterning induces a modulating dynamics of the contact line that causes an effective wetting, which in turn determines the modulation of the interface velocity. We characterize the modulation frequency in terms of wetting pattern, inertia, and surface tension, via the capillary pressure, viscosity, and confinement.

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I. INTRODUCTION

Fluid dynamics of multi-phase flows over rough, textured, or chemical patterned surfaces have a wide range of technological applications, for instance, self-cleaning,^{1,2} anti-fogging,^{3,4} the roll of water droplets down a surface while displacing air,⁵ the sliding of water drops on chemically heterogeneous surfaces,⁶ the dynamics of a fluid front during the capillary filling of a microchannel,^{7,8} providing adherent sites for cell growth in organs on chips,⁹ and metering discrete liquid volumes.¹⁰ One of the main usages of patterned surfaces is to control flow dynamics in microchannels,^{11–13} for instance, the capillary flow on laminated papers can be hold for a desired time by using patterns of inks with different levels of hydrophobicity,¹⁴ modulated penetration of a liquid can be achieved by using capillaries with hydrophilic–hydrophobic rings,¹⁵ and at specific positions, flow speed can be controlled by adjusting the ratio of hydrophobic area to whole channel width.¹⁶ Recent studies on unstable thin films with patterned

substrates were focused on finding ways in which they could be oriented toward preferred spatial paths. 17,18 Most studies of moving fronts have been done by driving the fluids by constant pressure drops. However, in some microfluidic devices, there are intentional or unintentional pulsatile forces, for instance, in systems involving droplets.^{19,20} Front dynamics subject to pulsatile forcing on patterned substrates has not been widely studied. Mondal et al.21 studied the contact line dynamics over patterned surfaces with wettability gradients under pulsating flow and analyzed the slip-stick behavior of the contact line movement in systems in which the interface runs through several patches of the wetting pattern during a period of the pulsation. In the present study, we analyze the dynamics of fluid-fluid interfaces within rectangular microchannels with patches of hydrophilic wetting in systems in which the interface oscillates several times within the pulsatile period over patches of hydrophilic or neutral wetting. We observed that the front advances with a stair-like modulation with characteristic regions in which the front velocity has two different regimes, related to the interface traveling over patches of different hydrophilicity. We characterized the modulation frequency found in the dynamics in terms of the combined effects of the wetting pattern, inertia, and surface tension, via the capillary pressure, viscosity, and confinement. Our results could be used to find ways in which pulsatile stable fronts in patterned substrates can be handled in order to control the way in which contact lines evolve. This would allow for controlling the residence times of stable fronts in desired regions of the microchannel.

II. MODEL AND NUMERICAL IMPLEMENTATION

We have recently introduced a phase-field model that takes inertia into account and provides a framework to study interfaces between two immiscible fluids subject to pulsatile forcing, where acceleration is always present. In this paper, we use this model to study the pulsatile interface dynamics, flowing over a patched substrate with patches of different wettability. Our periodic patterning consists of a hydrophilic region followed by a neutral one, both of the same size, see Fig. 1(a). There are different regimes of the front dynamics, depending on the nature of the hydrophilic patch. When hydrophilicity is low, the interface advances for a short period of time but then, it gets stuck in a patch of neutral wetting. For very hydrophilic patches, the front dynamics follows a classical Washburn behavior, $H \sim t^{1/2}$. We have chosen wetting values in a regime where the front dynamics presents a modulation induced by the spatial pattern of the wetting patches. The characterization of this phenomena is the subject of the present study.

The mesoscopic equation that we use to describe the interface dynamics is a phase-field model of the form:²²

$$\alpha \frac{\partial^2 \phi}{\partial t^2} + \frac{\partial \phi}{\partial t} = \nabla \cdot M \nabla \mu(\phi), \tag{1}$$

where ϕ is the order parameter, α is a parameter related to inertia, M is a mobility, $\mu(\phi) = -\phi + \phi^3 - \varepsilon^2 \nabla^2 \phi$ is the chemical potential, and ε is a parameter proportional to the interface width, see Appendix A for more details on this phase-field model. The following boundary condition is imposed at the entrance, x = 0, of the microchannel:

$$\mu(x = 0, t) = \mu_0 \cos(\omega_f t).$$
(2)

This represents the pulsatile driving force of the system, with frequency ω_{β} see Fig. 1(a) for a schematic representation of the pulsatile driving. The initial boundary condition is an equilibrium profile for the order parameter with a flat interface between the fluids. At the microchannel walls, we impose two boundary conditions; one of them ensures that there is no flow through them, $\hat{\mathbf{n}} \cdot \nabla \mu|_{z=0} = \hat{\mathbf{n}} \cdot \nabla \mu|_{z=L_z} = 0$, where $\hat{\mathbf{n}}$ is a unit normal vector to the walls. The second condition introduces a fluid–wall interaction as in Ref. 8 and allow us to create the wetting pattern,

$$\hat{\mathbf{n}} \cdot \nabla \phi \big|_{z=0} = \hat{\mathbf{n}} \cdot \nabla \phi \big|_{z=L_{x}} = A_{s}, \tag{3}$$

where A_s is a parameter that describes the preference of the wall for either the fluid ($A_s > 0$, for hydrophilic interactions) or the air (A_s < 0, for hydrophobic interactions). The case of neutral wetting corresponds to $A_s = 0$. The wetting pattern is created by imposing the boundary condition given by Eq. (3) with $A_s > 0$ in a region of n_P units of length, followed by a region with n_P units of length with neutral wetting, $A_s = 0$. In the sharp interface limit,²² this model gives $\nabla^2 p = 0$, for the bulk; and the boundary conditions at the fluid–fluid interface, namely, the local thermodynamic equilibrium condition, $\Delta p = -\sigma \kappa$, where Δp is the pressure drop across the interface, κ is its local curvature, and σ is the surface tension; and the continuity boundary condition, which requires the normal velocity of the interface, v_m to be equal to the normal velocity of the fluid at the interface, which satisfies



FIG. 1. (a) Schematic representation of the microchannel with a periodic wetting pattern used to integrate Eq. (1) subject to a pulsatile driving at the entrance. The interface curvature indicates the hydrophilic nature of the regions with wetting, represented with red lines. (b) Interface profiles for four halves of the driving cycle. The time arrow within each sub-figure goes from blue to black and from black to red. For the hydrophilic patches $A_s = 0.08$, for the neutral patches $A_s = 0.0$; $\mu_0 = 0.1$, $\omega_f = 0.0025$ and $\alpha = 400$.

$$\alpha \frac{\partial \mathbf{v}_n}{\partial t} + \mathbf{v}_n = -\frac{M}{2} \nabla p \cdot \hat{n}. \tag{4}$$

The last equation shows that the phase-field model leads to an acceleration term where the parameter α is related to density. We use this phase-field model since the second derivative in time of the order parameter accounts for inertia, which is relevant whenever the system is accelerated, as when driven by an oscillatory forcing. The phase field model parameters, *M* and α , can be related to physical ones using the Navier–Stokes equation for an incompressible Newtonian fluid, with viscosity, η , confined in a microchannel of height *b*. This allows one to identify *M*, as the steady state mobility, $\frac{M}{2} = \frac{b^2}{12\eta}$, just as in the model without the second derivative; and to relate α , with the fluid density, ρ , through $\alpha = \frac{6}{5} \frac{pb^2}{12\eta^2}$ Variables of the phase-field model are non-dimensional; therefore, to use the results of the phase field-model for a particular system, it is necessary to establish conversion factors, see Appendix B for conversion factors for water in a 300 μ m microchannel.

In a previous work,²² we found two different regimes that depend on the value of the product $\omega_f \alpha$, where ω_f is the angular frequency of the pulsatile pressure gradient. $\omega_f \alpha$ is a non-dimensional time, which involves viscous time and forcing frequency. For $\omega_f \alpha \ll 1$, inertia is irrelevant and the dynamic behavior is the one of the usual phase-field models without the second derivative in time. For $\omega_f \alpha \gg 1$, inertia is always relevant. In between these two regimes, there is a crossover region in which inertia is also relevant. We have chosen the values of ω_f and α in such a way that their product is equal to 1, in order to study the interface dynamics in a regime where inertia is relevant.²²

For many microfluidics systems, the rectangular cross section of the channels is such that the system can be considered quasi 2D and the rectangular geometry can be replaced by infinite parallel plates.^{23,24} We have carried out numerical integrations of Eq. (1) for the order parameter subject to the dynamic boundary condition given by Eq. (2) and a chemical (not morphological) wetting pattern in Eq. (3). We have used an Euler method for a quasi 2D discrete rectangular lattice of size $L_x L_y L_z$ with mesh size $\Delta x = \Delta y = \Delta z = 0.5$ and time step $\Delta t = 0.005$. The cell dimensions have been chosen as $L_x = 150$, L_y = 5, and L_z = 21. We have chosen periodic boundary conditions in y where we have no walls. Therefore, the system is practically two dimensional since it is infinite in the *y* direction. We track the interface position, defined as the locus of points for which the front has $\phi = 0$, as a function of time $H(z,t) \equiv x(z,t)|\phi = 0$. In addition, we compute the chemical potential field at any point in the system $\mu(x, z, t)$, which is equivalent to compute the pressure field.

III. INTERFACE DYNAMICS OVER PATTERNED SUBSTRATES

We track the interface position and observe that the presence of hydrophilic patches causes a different displacement between the two halves of the driving cycle. That is, when the pressure gradient pulls the interface, this one cannot be displaced as much as when the pressure gradient pushes the interface. This behavior can be appreciated by observing the interface shape in four half cycles in Fig. 1(b), the blue to black profiles correspond to pushing of the driving, and the black to red ones to pulling, respectively. We study the z-averaged position of the interface, $\langle H(t) \rangle_z$, for different patterning lengths and values of the wetting parameter.

In Fig. 2, we show the relevance of inertia in our numerical integrations for the choice $\alpha \omega_f = 1$. We plot the interface position as a



FIG. 2. Interface position as a function of time for a microchannel with patterning P 3-3, hydrophilic patches of $A_s = 0.05$, and two values of α . The figure shows that in the absence of inertia, the interface get stuck; while when inertia is taken into account, the front keeps advancing. For these results, $\mu_0 = 0.1$ and $\omega_f = 0.0025$.

function of time of a hydrophilic microchannel with a wetting patterning 3–3 (P 3–3), namely, one in which a hydrophilic patch of three unit lengths $n_p = 3$ is followed by a neutral patch of three unit lengths $n_p = 3$, such that the length of the pattern is $2n_p = 6$. When there is no inertia, as the red line in Fig. 2 shows, the interface gets stuck in a patch of neutral wetting; while when there is inertia, as the blue line in Fig. 2 shows, the front can proceed to the next hydrophilic patch.

Figure 3(a) shows, in gray, the interface position as a function of time of a hydrophilic microchannel with uniform wetting parameter $A_s = 0.08$ and, in red, the interface position as a function of time of a hydrophilic microchannel with a wetting patterning 1-1 (P 1-1). Clearly, in this case, the front advancement is slower, since only half of the substrate pulls the front. For reference, we plot, in blue, the interface position as a function of time of a hydrophilic microchannel with uniform wetting parameter $A_s = 0.04$ that corresponds to the spatial average of the patterned substrate with $A_s = 0.08$ and $A_s = 0.0$. We observe that the advancement of the blue and the red lines is undistinguishable. Figure 3(b) shows the interface position as a function of time for microchannels with four different patterning lengths, $2n_p$, with $n_p = 1, 2, 3$, and 4. It can be observed that the smaller the patterning length, the faster the front advancement and, more important, that the front dynamics presents a stair-like modulation, with characteristic regions in which the front velocity has two different values, corresponding to the interface traveling over the hydrophilic or the neutral patch. The stair-like dynamics of the front advancement can be understood with the local hydrophilicity/neutrality of the chemical patches. Figure 3(c) shows the front advancement in the form H^2 vs t from the numerical integration and reference lines, for the main slopes of the stair, corresponding to the expression $H^2 = b\sigma \cos \left[\theta_d\right]/(3\eta)t$ (given by the viscous Washburn regime²⁵) for which we have taken the minimum and maximum values of the cosine of the dynamic contact angle from Fig. 4 and a surface tension parameter of 0.46.³

IV. CONTACT LINE DYNAMICS AND EFFECTIVE WETTING

We quantify the contact angle dynamics³⁹ and illustrate it in Figs. 4(a)-4(d). It can be noticed that the global dynamics of the contact angle is modulated, as expected from the patterning imposed by

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(a)



FIG. 3. Interface position as a function of time. (a) For three different microchannels: uniform hydrophilic substrate with $A_s = 0.08$, uniform hydrophilic substrate with $A_s = 0.04$, and patterned substrate P 1-1. (b) For four microchannels with different patterning lengths: P 1-1; P 2-2; P 3-3; P 4-4. For these results, $\mu_0 = 0.1$, $\omega_f = 0.0025$, and $\alpha = 400$. (c) Squared interface position as a function of time for a pattern P 4-4. Reference lines, for the main slopes of the stair, are given by $H^2 = b\sigma \cos [\theta_d]/(3\eta)t$, with minimum and maximum values of cos $[\theta_d]$.

the substrate and inertia. As reference, we show, with red dots, the average value of $\cos [\theta_d(t)]$ between maxima and minima of the modulation, this one, decreases with the increase in patterning length. This causes the front to advance slower for large patterning lengths, for

which inertia keeps the front advancement in neutral patches. For very large patterning lengths, inertia would not be enough to sustain the movement of the front. Also, as reference, the cosine of the static contact angle, θ_s , is plotted with continuous black line, for the spatially

FIG. 4. Cosine of the dynamic contact angle (blue line) and its average in half cycles (red dots) as a function of time for (a) pattern 1-1, (b) pattern 2-2, (c) pattern

3-3, and (d) pattern 4-4, chosen to illustrate different modulations. In each plot, for

reference, the cosine of the static contact angle θ_s for the spatially averaged wetting parameter is shown (black line). For the hydrophilic patches $A_s = 0.08$; $\mu_0 = 0.1$, $\omega_f = 0.0025$, and $\alpha = 400$.



averaged wetting parameter. In a uniform substrate, the static contact angle, θ_s is related to the value of the wetting parameter, A_s , ^{26,27} as

$$\cos\left[\theta_{s}\right] = \frac{1}{2} \left[\left(1 + A_{s}\right)^{3/2} - \left(1 - A_{s}\right)^{3/2} \right].$$
 (5)

Here, we define an effective wetting, A_{eff} through an equivalent analytical expression that relates it to the dynamic contact angle, θ_d , through

$$\cos\left[\theta_{d}\right] = \frac{1}{2} \left[\left(1 + A_{eff}\right)^{3/2} - \left(1 - A_{eff}\right)^{3/2} \right].$$
(6)

It can be demonstrated by a Taylor series expansion that for small values of the wetting parameter, $\cos [\theta_d]$ and A_{eff} are proportional to each other. In Fig. 5(a), we quantify the effective wetting and observe its dynamics, which also presents a sequence of peaks and valleys (observed for $\cos [\theta_d(t)]$). We also show the front position as a function of time (blue line indicated, with $\phi = 0.0$) and observe that when the effective wetting is maximum, the front position presents a smooth jump and advances faster. Since we work with a diffuse interface, we show, in green, that the global behavior of the front advancement for $\phi = -0.8$ (the upstream interfacial region) has the same qualitative behavior that the interface position.

As reference, the position of the hydrophilic patches is shown with red lines over the y-axis. It can be observed that each time that the effective wetting reaches a peak, there is a jump in the interface position as a function of time.



FIG. 5. (a) Front position as a function of time for $\phi = 0$ (blue line) and for $\phi = -0.8$ (green line), the effective wetting is shown in magenta. The position of the hydrophilic patches is shown with red lines over the y-axis. (b) Global velocity of the interface as a function of time for $\phi = 0$ (blue line) and for $\phi = -0.8$ (green line); and effective wetting (in magenta). For these results, the pattern is 3-3; the hydrophilic patches have $A_s = 0.08$; $\mu_0 = 0.1$, $\omega_f = 0.0025$, and $\alpha = 400$.

In Fig. 5(b), we show the global velocity of the z-averaged position of the front for $\phi = 0$ and $\phi = -0.8$. The time interval where the interface is on a hydrophilic patch is shown over the x-axis. It can be observed that the upstream position of the front arrives first to the hydrophilic patches. However, there is practically no difference for the velocity of the blue and green curves. Figure 5(b) also shows in magenta, the effective wetting parameter and, a comparison of this, with blue and green curves, demonstrates that the modulation of the front global velocity follows closely the one of the effective wetting.

V. INTERFACIAL PRESSURE AND MODULATION FREQUENCY

The modulation frequency can be explained by realizing that a natural characteristic frequency could be written as the ratio of the average velocity on a period, and a parameter accounting for the characteristic patterning size, that is, $\nu = \frac{\langle v \rangle}{2n_0}$, which can be written as

$$\nu = \frac{1}{2n_p} \frac{b^2}{12\eta} \frac{|p_{int}|}{|H_{int}|},\tag{7}$$

where $\langle v \rangle$ has been taken as the average velocity on a period, according to Eq. (4). $|p_{int}|$ and $|H_{int}|$ are the average in *z* and half-cycles in time, of the pressure at the interface and the interface position, respectively.

Pressure at the interface is a capillary pressure that can be written in terms of a dynamic contact angle. Figure 6(a) shows (in green) the pressure at the interface and (in blue) the capillary pressure, given by the cosine of the dynamic contact angle $2\sigma \cos [\theta(t)]/b$, as a function of time. We can observe that they are on phase, have exactly the same period, and their averages, indicated by the orange and yellow dots, are undistinguishable. Figure 6(b) illustrates such undistinguishability, for different



FIG. 6. (a) Pressure at the interface and capillary pressure $2\sigma \cos{[\theta(t)]}/b$ as a function of time. For a 3-3 pattern with hydrophilic patches with $A_s = 0.08$. Half-period averages of both quantities (shown with dots) are undistinguishable. (b) Half-period averages of pressure at the interface and capillary pressure for different patterns. The darker the dot color, the larger the time.

patterning sizes. Lighter dots correspond to early cycles in time, and darker dots correspond to longer times. The dots evolve in time due to the front getting away from the forcing source. With this, we could write Eq. (7) as

$$\nu = \frac{b\sigma \cos\left[\theta_d\right]}{12\eta \, n_p |H_{int}|}.\tag{8}$$

In Fig. 7, we compare the modulation frequency obtained from the interface position (y-axis) and the one estimated by Eq. (8) (x-axis) for different patterned substrates and different values of the wetting parameter. The slope m = 1 is indicated with a continuous line. This result shows that the modulation frequency is determined by the combined effects of wetting pattern, inertia, and surface tension, via the capillary pressure, viscosity, and confinement.

We have corroborated that the modulation frequency is also related to the time that the interface needs to return to a given shape. Due to the combined effect of fluid inertia, wetting and driving, the interface does not come back to the same shape after one cycle of the driving but after one cycle of the modulation. The corresponding period is the time that the front takes to arrive to an equivalent position of a patch downstream. In this one, the interface shape is not exactly identical as in the previous one, but almost identical, due to the fact that it has moved away from the forcing source.

VI. DISCUSSION

We have studied the pulsatile dynamics of fluid–fluid interfaces within rectangular microchannels with patches of hydrophilic wetting on the walls of the confining media. We find that the front advances with a stair-like modulation with characteristic regions in which the front velocity has two different values, related to the interface traveling over patches of different hydrophilicity. This result differs from the presented in Mondal *et al.*,²¹ where they found a flow reversal phenomena related to the pulsation. In our case, the flow reversal related to the pulsation is negligible when compared to the stair-like front advancement. We found that the contact angle also presents a modulation and that the cosine of the contact angle can be related to an effecting wetting. The effective wetting parameter has an oscillatory dynamics whose maxima coincides with jumps in the interface position and maxima of the interface velocity.



FIG. 7. Comparison between the modulation frequency, measured from the interface position, and the one obtained with Eq. (8). The slope, m = 1, is shown with a continuous line.

We characterize the modulation frequency through a characteristic frequency given by the front velocity, averaged in a period, and the patterning size. Pressure at the interface can be written in terms of a dynamic contact angle. This allows us to know that the modulation is due to the combined effects of the wetting pattern, inertia, and surface tension, via the capillary pressure, viscosity, and confinement.

Note that this modulation frequency is different than the selected frequency found in many pattern selection systems (see, for example, the work of Ledesma-Aguilar et al.²⁸). For those ones, a particular frequency is chosen by the system, independently of which is the driving frequency, and the driving frequency itself does not appear in the stationary state. In our system, the front is subject to two frequencies, the one of the forcing and one due to the substrate patterning. We find that the driving frequency is always present in the dynamics of the front advancement and that a modulation frequency appears both in the front advancement and in the contact line dynamics. We have characterized this modulation frequency in terms of the system parameters. In Appendix B, we show conversion factors for water in a $300 \,\mu\text{m}$ microchannel, allowing one to determine in which experimental conditions, our results could be confirmed. For example, to experimentally reproduce the results of Fig. 3(b) for a 4-4 patterned microchannel, one could take water in a $300 \,\mu\text{m}$ high microchannel with alternating patches of 57.2 μ m each of hydrophilic-neutral wetting and use a pulsatile pressure of amplitude equal to 1 Pa, with a frequency of 18 Hz during 22.4 s. According to our model, we will observe a stairlike modulation, with approximately three steps with a total interface displacement of 500 μ m, which is within the experimental capabilities to measure displacements in microfluidics. These results have potential applications in the control of pulsatile microfluidic interfaces.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

APPENDIX A: PHASE-FIELD MODEL

The phase-field model that we use is an extension of the Cahn-Hilliard model that has been extensively used in the literature.^{8,29–33}

Phase field model (PFM) parameter	Numerical value of the PFM Parameter with "PFM units"	Macroscopic value in IS units	Conversion factor
b	$21 U_L$	$3 imes 10^{-4}\mathrm{m}$	$f_L = 1.43 imes 10^{-5} { m m}/U_L$
М	$1 U_M$	$2b^2/(12\eta) = 1.50 imes 10^{-5} \mathrm{m^3 s/kg}$	$f_M = 1.50 imes 10^{-5} { m m}^3 { m s}/({ m kg} U_M)$
α	$400 \ U_t$	$ ho b^2/(10\eta)=8.98 imes 10^{-3}{ m s}$	$f_t = 2.24 imes 10^{-5} { m s}/U_t$
$b^2/(6M)$	73.5 U_{η}	$\eta = 0.001 \mathrm{kg}/(\mathrm{ms})$	$f_{\eta} = 1.36 \times 10^{-5} \mathrm{kg}/(\mathrm{m s} U_{\eta})$
$5\alpha/(3M)$	666 $U_{ ho}$	$ ho=998\mathrm{kg}/\mathrm{m}^3$	$f_ ho = 1.50\mathrm{kg}/(\mathrm{m^3}~U_ ho)$
μ_0	$0.1 U_{p_0}$	$p_0 = 1 \mathrm{kg}/\mathrm{ms}^2$	$f_p = 10 { m kg}/({ m ms}^2 U_{p_0})$

TABLE I. Conversion factors for water in a channel of height 300 μ m.^a

^aNote that only four of these parameters are independent. The conversion factor for viscosity and density can be obtained from the first three parameters. On the other hand, the value of surface tension used in the reference lines of Figs. 3(c), 6, and 7, was $0.46U_{\sigma}$, which for an air-water interface is $\sigma = 0.072$ N/m, giving a conversion factor of $f_{\sigma} = 0.1565$ N/(m U_{σ}).

The latter consists of a time-dependent equation for a conserved order parameter (ϕ) derived from the minimization of a double-well Ginzburg-Landau free energy of the form

$$\mathcal{F}[\phi] = \int d\mathbf{r} \left[-\frac{\phi^2}{2} + \frac{\phi^4}{4} + \frac{(\varepsilon \nabla \phi)^2}{2} \right]. \tag{A1}$$

This one allows for the coexistence of two phases and the existence of the interface. The extension of the model introduced in Flores Gerónimo *et al.*²² and used in the present work for substrates with chemical patterns accounts for inertia, which is relevant in accelerated systems, like the ones subject to pulsatile forcing. The dynamic equation for the order parameter is given by

$$\alpha \frac{\partial^2 \phi}{\partial t^2} + \frac{\partial \phi}{\partial t} = \nabla \cdot M \nabla \mu(\phi), \tag{A2}$$

where α is a parameter related to inertia and *M* is a mobility,

$$\mu(\phi) = -\phi + \phi^3 - \varepsilon^2 \nabla^2 \phi \tag{A3}$$

is a chemical potential, and ε is a parameter related to the interface width. We use $\varepsilon = 1$, a value that has been used in other works,^{8,28,34,35} and it is small enough so the results do not depend on its value.³⁶

One of the main advantages of the phase-field models is to overcome the free-boundary problem presented in moving boundary conditions, avoiding complicated methods for tracking the interface position. Moreover, their computational implementation is usually very easy.

APPENDIX B: CONVERSION FACTORS

Variables of the phase-field model are non-dimensional; therefore, to use the results of the phase field-model for a particular system, it is necessary to establish conversion factors. As an example, take a channel of height 300 μ m and density, viscosity and surface tension of water: $\rho = 998 \text{ kg/m}^3$, $\eta = 0.001 \text{ kg/(ms)}$ and $\sigma = 0.072 \text{ N/m}$. Table I shows conversion factors for lengths, time, viscosity, density, surface tension, and pressure.

We can convert the pulsatile angular frequency in the phasefield, $\omega_f = 0.0025$, to a macroscopic value of frequency in Hz using the conversion factor for time (related to the parameter α); it is $\nu = 0.0025/(2\pi 2.24 \times 10^{-5} \text{s}) = 18 \text{ Hz}.$ The capillary pressure for a wide microchannel is $p_c = 2\sigma \cos [\theta_s]/b$, the capillary pressure is 58 Pa with the cosine of the static contact angle corresponding to the spatially averaged wetting parameter, shown with black lines in Fig. 4. A pressure of the order of 1 Pa at the microchannel entrance represents only 1.7% of the capillary pressure.

Thus, as stated in the text, this means that for water in a $300 \,\mu\text{m}$ microchannel with a 4-4 pattern, a pulsatile pressure of amplitude equal to 1 Pa, and a frequency of 18 Hz imposed during 22.4 s, we will observe a stair-like modulation, with approximately three steps and an interface displacement of $500 \,\mu\text{m}$, which is within the experimental capabilities to measure displacements in microfluidics.

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