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Wall slip and fluidity in emulsion flow

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The microscopic origin of apparent wall slip is studied systematically using a confocal laser scanning microscope coupled to a rheometer. We obtain flow curves on a model emulsion from classical macroscopic measurements that are compared with flow curves obtained from microscopic measurements. By controlling the wetting properties of the shearing walls, we show that the characteristic length used in the so-called fluidity model, proposed by Goyon *et al.* [*Nature (London)* **454**, 84 (2008)], can be understood in terms of roughness induced by adsorbed droplets on the surface. Additionally, we disentangle two different effects that contribute to the difference between micro- and macrorheology. Both effects manifest themselves as gap-dependent viscosities due to either the formation of a lubricating layer close to the shearing walls or cooperative effects when the flow is strongly confined. Finally, we show that the cooperative effects can also be translated into an effective slip velocity.

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The boundary conditions for the Navier-Stokes equation describing fluid flows have been debated ever since the original paper of Navier appeared in 1823 [1]. For simple (Newtonian) fluids, a no-slip boundary condition is sufficient for most practical situations; however, the increasing miniaturization of flow devices has led to further debate on this issue [2]. Wall slip has been reported for concentrated dispersions such as emulsions, foams, or gels. This has resulted in misinterpretations of rheology data, and it has become a limiting factor in production processes such as fiber spinning or food extrusion [3–6].

In addition, confinement may affect the flow of concentrated dispersions in an entirely different fashion, namely through collective rearrangements of the dispersed phase. This can be accounted for using the recently proposed fluidity model [7], which introduces a length scale (ξ) characteristic of the spatial cooperativity that is at the origin of the spatial variation of the viscosity (η). The fluidity f is the inverse of the viscosity ($f = 1/\eta$), and its spatial variation, considering a fluid flowing in the x direction, can be modeled as $f = f_{\text{bulk}} + \xi^2 \frac{\partial^2 f}{\partial z^2}$, where f_{bulk} is the fluidity of the bulk and z is the coordinate perpendicular to the x - y plane. This implies that in the absence of any cooperativity, the fluidity would reduce to its bulk value, $f_{\text{bulk}} = \dot{\gamma}/\sigma_{\text{bulk}}$, where σ_{bulk} is the shear stress at the bulk.

It has been reported that slip and confinement affect the stability of two-phase flows in microfluidic channels [8]; when considering the flow of concentrated dispersions, both effects lead to gap-dependent viscosities, which in rheology is usually interpreted as wall slip [3,6].

In rheology, an apparent viscosity that depends on the dimensions of the measuring device is usually interpreted in terms of wall slip (see, e.g., [9]) without assuming anything about the involved physical mechanism. The slip length in the classical sense as introduced by Mooney [10] is then simply a way of correcting the gap dependence of the viscosity. The most commonly accepted mechanism is that there is a layer of different viscosity material close to the shearing walls [3]. When considering nonlocal viscosity, the effect is the same as that of wall slip, i.e., the macroscopically measured viscosity becomes a function of the gap size. However, the so-called fluidity model [7] supposes a viscosity that continuously varies

in space and that is due to local rearrangements. For example, Bocquet *et al.* [11] claim that the fluidity model equation “yields a nonlocal constitutive law for the flow, exhibiting as a key dynamic quantity the local rate of plastic rearrangements.” Therefore, the interpretation in the two situations, namely wall slip and nonlocal viscosity, is very different [7,9].

In this paper, we perform local measurement of the velocity profiles for two different boundary conditions near the wall and in three different geometries. We conclude that, when fluidity becomes important, the results can also be interpreted in terms of wall slip. This is because the cooperativity length scale is microscopic, and it changes the velocity profile only very close to the wall, on a length scale comparable to the size of the emulsion droplets. A detailed local study of the wall slip by changing the boundary condition shows that the relevant length scale for slip is also the emulsion drop size.

Our model system is a transparent silicone oil-in-water emulsion that allows for flow visualization. It has an average drop size $5\ \mu\text{m}$, internal volume fraction $\phi \approx 0.80$, and 21% polydispersity [12,13]. Macroscopic rheology data are obtained using a rheometer (Anton Paar MCR 301) with cone-plate (CP) and plate-plate (PP) geometries. The cone has a 12.5 mm radius and 1° , while the plates in the plate-plate geometry have a 12.5 mm radius. For Newtonian fluids, the CP geometry admits nearly uniform shearing flows, i.e., spatial shear stress (σ) and shear rate ($\dot{\gamma}$) that are nearly uniform, as described by [9]; in addition, the PP geometry enables us to work with different gaps (w). Microscopic rheological measurements are performed using a confocal microscope (Zeiss Pascal Live) coupled to a rheometer (Anton Paar DSR 301) that enables the acquisition of velocity profiles in the flowing material by direct visualization of the droplet motion. This is done by looking through the bottom plate of both CP and PP geometries, in which the cone of the CP geometry has a 6 mm radius and a 2° angle, while the upper plate of the PP geometry has a 4 mm radius. Finally, for comparing our results with those obtained by Goyon *et al.* [7,14], we also acquire velocity profiles in glass microchannels. In all cases, from the measured local velocity gradient ($\dot{\gamma}_{\text{local}}$) and stress (σ_{local}) we obtain the *local viscosity*.

The bottom plates of the CP and PP geometries and the walls of the microchannels consist of chemically treated glass. Hydrophilic surfaces are obtained by cleaning the glass with piranha solution (70% v/v sulfuric acid and 30% v/v hydrogen peroxide, both from Sigma Aldrich), according to the following procedure: (i) sonicate the glass for 15 min in a 10% Decon 90 aqueous solution, (ii) rinse the glass with water, (iii) immerse it in piranha solution for 15 min at 150 °C, (iv) rinse the glass with water, and (v) dry the glass in the oven at 200 °C for 1 h. Additionally, hydrophobic surfaces are prepared by treating the glass with a hydrogenated silane (Dynasylan ® from Degussa), according to the following silanization procedure: (i) bring the glass treated with piranha solution and dried in the oven to room temperature in a desiccator, (ii) immerse the glass in a silane solution for 30 min, (iii) rinse the glass with isopropanol (from Sigma Aldrich), and (iv) dry the glass in the oven at 75 °C for 1 h [15,16]. The upper plate of the PP geometry consists of a hydrophobic glass slide, while the CP geometry has a roughened cone. The modification of the wetting properties is confirmed by measuring the equilibrium contact angle (θ) of the treated glass surfaces with silicone oil and the continuous phase of our emulsion surrounded by air. We also measure the equilibrium contact angle of silicone oil with the hydrophobic surface surrounded by the continuous phase ($\theta \approx 43 \pm 1^\circ$). As the oil does not stick to the hydrophilic surface surrounded by the continuous phase, $\theta \approx 180^\circ$. Macroscopic measurements consist of shear rate sweeps. Figure 1 shows that hydrophobic plates completely suppress wall slip, as the flow curves coincide with a reference curve obtained using roughened surfaces; the latter is a standard method to prevent wall slip [6]. These curves are well described by the classical Herschel-Bulkley equation [17]: $\sigma = \sigma_y + K\dot{\gamma}^n$, where σ_y is the yield stress, and K and n are model adjustable parameters. This model is known to work

well for emulsions in the absence of wall slip [12]. Conversely, for hydrophobic plates at smaller gaps ($w \lesssim 50 \mu\text{m}$), but also for the hydrophilic ones, we observe different and in addition gap-dependent viscosities, as shown in Fig. 1. As will be shown later in Fig. 2, when performing rheological measurements using hydrophilic lower plates, almost all of the sample moves as one solid block with the same speed of the upper plate (or cone).

Interestingly, for the hydrophobic plates, the flow curves can also be fitted to the Herschel-Bulkley model, with the same K and n parameters given by the fit of the reference flow curve; these fits are not shown, but the values of the fitting parameters are shown in Table I. It is worth noting that the values of σ_y given by the Herschel-Bulkley fit of the flow curves at $w = 50$ and $30 \mu\text{m}$ would correspond to emulsions having a lower internal volume fraction [18], i.e., a flow curve at $w = 50 \mu\text{m}$ would correspond to emulsions having an internal volume fraction $\phi \approx 0.77$ with $\sigma_y \approx 28.90$ Pa, while a flow curve at $w = 30 \mu\text{m}$ would correspond to emulsions having an internal volume fraction $\phi \approx 0.74$ with $\sigma_y \approx 16.80$ Pa. Therefore, a person performing rheological measurements using our model system in a gap $w \lesssim 50 \mu\text{m}$ would, wrongly, think that either the yield stress of the sample having $\phi \approx 0.80$ is much lower than 33.32 Pa, or that the sample has an internal volume fraction $\phi < 0.80$.

Microscopic measurements show that the surface wettability is key for the boundary conditions. We perform experiments using the CP and PP geometries, observing a uniform $\dot{\gamma}$ for hydrophobic plates at large gaps, as observed for Newtonian fluids. However, when using hydrophilic plates, the material turns as a solid block with the moving upper cone or plate [Figs. 2(b) and 2(c)].

We also perform local velocity measurements in microchannels ($w = 400 \mu\text{m}$), for which there is a spatial variation of the stress [7,14]. For these, the results are similar [Fig. 2(a)]: we observe “plug flows” for hydrophilic walls, while for hydrophobic ones we obtain velocity profiles that are perfectly described by the Herschel-Bulkley model, taking into account the stress variation over the channel [19] [see Eq. (1)] and with the same parameters used for fitting the reference flow curve in Fig. 1, i.e., $\sigma_y = 33.32$ Pa, $K = 13.43 \text{ Pa s}^{0.53}$, and $n = 0.53$,

$$V = \frac{(w/2)}{(1/n + 1)} \frac{1}{\sigma_w K^{1/n}} \times \left\{ [\sigma_w - \sigma_y]^{1/n+1} - \left[\sigma_w \frac{(w/2) - z}{(w/2)} - \sigma_y \right]^{1/n+1} \right\}, \quad (1)$$

where σ_w is the stress at the wall, w is the capillary width, and z is the length in the Z coordinate. The stress at the wall was obtained using Eq. (2), considering the imposed flow rate (Q),

$$Q = \frac{2b(w/2)^2}{(1/n + 1)\sigma_w^2} \frac{(\sigma_w - \sigma_y)^{1/n+1}}{K^{1/n}} \left\{ \frac{[\sigma_w(1/n + 1) + \sigma_y]}{(1/n + 2)} \right\}, \quad (2)$$

where b is the capillary breadth.

We now investigate the microscopic origin of this slip/no-slip behavior. Figure 2(d) shows that half-spherical oil droplets stick to the hydrophobic glass surfaces, resulting in a “self-generated roughness.” This completely suppresses wall slip,

FIG. 1. (Color online) Macroscopic flow curves using hydrophilic and hydrophobic glass plates in CP and PP geometries, obtained from standard rheological measurements. Red symbols correspond to hydrophobic plates and blue symbols to hydrophilic plates. The black line is a fit of the flow curve (black symbols) obtained using roughened surfaces to the Herschel-Bulkley model [17], with $\sigma_y = 33.32$ Pa, $K = 13.43 \text{ Pa s}^{0.53}$, and $n = 0.53$.

FIG. 2. (Color online) Microscopic measurements using a confocal laser scanning microscope coupled to a rectangular microchannel and to a rheometer. (a), (b), and (c) Velocity profiles in (a) rectangular microchannel (length $L = 10$ cm, breadth $b = 4$ mm, and width $w = 400 \mu\text{m}$) at 0.2 , 0.5 , and 1.2×10^{-2} mL/min (from bottom to top curves); (b) PP geometry (3.5 mm radius, gap $w = 100 \mu\text{m}$) and imposed overall shear rates 0.25 , 0.5 , and 1 s^{-1} , measured at a radial position where the measured local shear rates are 0.11 , 0.24 , and 0.48 s^{-1} (bottom to top); and (c) CP geometry (6 mm radius and 2° angle, measured at a radial position equivalent to a gap $w = 90 \mu\text{m}$) and imposed shear rates 0.25 , 0.5 , and 1 s^{-1} (bottom to top). (d) and (e) Microscopic origin of the wettability dependence of wall slip: (d) microscopic image showing that droplets of the flowing emulsion stick to hydrophobic glass surfaces, resulting in “self-generated roughness,” and (e) the same droplets do not stick on hydrophilic glass surfaces, leading to wall slip. In (a) blue symbols and lines correspond to hydrophilic surfaces, and red symbols and lines correspond to hydrophobic surfaces, in which the red lines represent the fitting of the profiles to the Herschel-Bulkley model considering the stress variation over the channel. In (b) and (c) blue symbols and lines correspond to hydrophilic surfaces, and red symbols and lines correspond to hydrophobic surfaces. Flow in the rectangular microchannel is induced using a syringe pump, while a rheometer is used to induce a deformation in the model emulsion by rotating either a cone or a plate. In (d) and (e) images in the X-Y plane are taken at $z = 0 \mu\text{m}$, the black bar is $20 \mu\text{m}$, and arrows are $10 \mu\text{m}$.

similarly to what happens for roughened surfaces (Fig. 1). Conversely, for hydrophilic systems, Fig. 2(e) shows that a thin layer of water is present at the surface, which induces an effective slip of the emulsion.

However, in hydrophobic systems without wall slip, gap-dependent viscosities are also observed. In the CP and PP geometries, for $w \gtrsim 50 \mu\text{m}$, neatly linear velocity profiles

that extrapolate to zero at the stationary wall are obtained [Figs. 2(b) and 2(c)]. For $w \lesssim 50 \mu\text{m}$ in the PP geometry, although the velocity profiles extrapolate to zero—at the bottom plate the oil droplets stick to the glass surface—they are nonlinear [Figs. 3(a) and 3(b)]. This indicates that the viscosity varies spatially, since σ_{local} is constant and $\dot{\gamma}_{\text{local}}$ varies.

TABLE I. Herschel-Bulkley parameters of flow curves shown in Fig. 1, when using a hydrophobic lower plate.

Geometry	σ_y Pa	K Pa s ^{<i>n</i>}	<i>n</i>
CP	33.32	13.43	0.53
PP 100 μm	33.32	13.43	0.53
PP 50 μm	28.90	13.43	0.53
PP 30 μm	16.78	13.43	0.53

From the velocity profiles, we obtain the *local flow curves* shown in Fig. 4 [20], which are the result of plotting σ_{local} as a function of $\dot{\gamma}_{\text{local}}$. Figure 4 shows that the local flow curves only correspond to the reference flow curve above a critical gap size. Below this size, we again find gap-dependent and different viscosities, as for a given σ_{local} different values of $\dot{\gamma}_{\text{local}}$ are obtained.

Velocity profiles in Fig. 3 were fitted considering the fluidity model [14,21], taking as a starting point the fluidity model equation:

$$\xi^2 \frac{d^2 f}{dz^2} + f_{\text{bulk}} - f = 0, \quad (3)$$

where f_{bulk} is the fluidity of the bulk emulsion at the applied σ and corresponding $\dot{\gamma}$.

Equation (3) is solved with the boundary conditions: (i) at the static lower plate, i.e., at $z = 0$, the fluidity is denoted as f_{LP} ; (ii) at the moving upper plate, i.e., at $z = w$, the fluidity is denoted as f_{UP} ; and (iii) as the upper plate is always hydrophobic, wall slip is not present at this surface, and the fluidity is assumed to be that of the bulk, thus $f_{\text{UP}} = f_{\text{bulk}}$. Solving Eq. (3) yields

$$f = f_{\text{UP}} + (f_{\text{UP}} - f_{\text{LP}}) \frac{\sinh[(z - w)/\xi]}{\sinh(w/\xi)}. \quad (4)$$

By integrating Eq. (4), the velocity field $v(z)$ is determined as $dv/dz = \sigma f(z)$. Then

$$v(z) = V_0 + (z - w)\dot{\gamma}_{\text{UP}} + \frac{\xi(\dot{\gamma}_{\text{UP}} - \dot{\gamma}_{\text{LP}})}{\sinh(w/\xi)} \left\{ \cosh\left[\frac{(z - w)}{\xi}\right] - 1 \right\}, \quad (5)$$

where V_0 is the velocity of the upper plate, $\dot{\gamma}_{\text{UP}}$ is the shear rate at the upper plate (corresponding to the locally imposed shear rate), and $\dot{\gamma}_{\text{LP}}$ is the shear rate at the lower plate.

From the fits of flow curves shown in Fig. 3 to Eq. (5), the characteristic length scale $\xi \approx 4.5 \pm 0.7 \mu\text{m}$ and $\dot{\gamma}_{\text{LP}}$ are obtained; it should be noted that ξ is the same for all fits shown in Fig. 3 and on the order of the droplet diameter.

Additionally, with the values of $\dot{\gamma}_{\text{LP}}$ and $\dot{\gamma}_{\text{UP}}$ the fluidities at the upper and lower plates are determined as $f = \dot{\gamma}/\sigma$. To do this, shear stress was determined by performing macroscopic rheological measurements, which consist in imposing the *locally* imposed shear rate and measuring the corresponding shear stress; these measurements were performed using the same surfaces used to perform the microscopic measurements. The values of the fluidities at the upper and lower plates are shown in Table II. This table shows that the fluidity is higher

FIG. 3. (Color online) Velocity profiles using a PP geometry in (a) gap $w = 50 \mu\text{m}$ and (b) gap $w = 30 \mu\text{m}$. Blue symbols and dashed lines correspond to hydrophilic surfaces. Red symbols correspond to hydrophobic surfaces, and red lines correspond to the fittings of the velocity profiles using the fluidity model, with $\xi \approx 4.5 \pm 0.7 \mu\text{m}$. The black line is referential to the velocity profile that would be obtained in the absence of cooperative effects. The dashed-gray lines are the fittings of the curves after transforming cooperative effects into an effective slip velocity. The same overall shear rates were imposed in both gaps, from bottom to top: 0.25, 0.5, and 1 s^{-1} . Profiles were measured at a radial position where the locally imposed shear rates, from bottom to top, are 0.11, 0.24 and 0.48 s^{-1} ; at this radial position, the velocity of the upper plate was 5.5, 12, and $24 \mu\text{m/s}$, respectively, for $w = 50 \mu\text{m}$, and 3.3, 7.2, and $14.4 \mu\text{m/s}$, respectively, for $w = 30 \mu\text{m}$.

at the lower plate than at the upper plate, which indicates that the shear rate is higher at the stationary bottom plate thanks to the noncooperative effects induced by the fluidity field, as described in [7].

The fact that this characteristic length scale, $\xi \approx 4.5 \pm 0.7 \mu\text{m}$, for the spatial variation of the viscosity is so small explains why when the gap becomes large compared to ξ , the effect of the fluidity becomes negligible.

FIG. 4. (Color online) Microscopic flow curves obtained from the velocity profiles using a hydrophobic microchannel as well as hydrophobic plates in CP and PP geometries. The black line is the fit of collapsing curves to the Herschel-Bulkley model used as a reference.

In addition, the velocity profiles shown in Fig. 3 can also be fitted to the standard equation for wall slip with a linear velocity profile that does not extrapolate to zero [3]: $v(z) = V_s + \dot{\gamma}_{\text{bulk}} z$. In our experiments, the shear rate of the bulk is given by $\dot{\gamma}_{\text{bulk}} = \sigma f_{\text{bulk}}$ and $f_{\text{bulk}} = f_{\text{UP}}$.

The net effect of wall slip or confinement is a decrease in the effective viscosity. The reduction of the viscosity of our model system with the gap size can be compared with granular materials, for which spatial cooperativity manifests itself identically as gap-dependent viscosities, if these materials are sheared in gaps ten times the particle size or smaller [22].

TABLE II. Fluidities at the upper plate (f_{UP}) and at the lower plate (f_{LP}) at different gaps (w) and imposed shear rates ($\dot{\gamma}_{\text{imp}}$) in a PP geometry. In all cases, $\xi \approx 4.5 \mu\text{m}$.

$\dot{\gamma}_{\text{imp}}$ (s^{-1})	f_{UP}	f_{LP}
	(Pa $^{-1}$ s $^{-1}$)	
	$w = 50 \mu\text{m}$	
1.00	$1.0 \times 10^{-2} \pm 1.2 \times 10^{-4}$	$2.4 \times 10^{-2} \pm 1.8 \times 10^{-3}$
with $\sigma_{\text{local}} = 42.3 \text{ Pa}$		
0.50	$5.6 \times 10^{-3} \pm 5.2 \times 10^{-5}$	$1.6 \times 10^{-2} \pm 1.6 \times 10^{-3}$
with $\sigma_{\text{local}} = 38.2 \text{ Pa}$		
0.25	$2.6 \times 10^{-3} \pm 8.5 \times 10^{-5}$	$1.1 \times 10^{-2} \pm 1.1 \times 10^{-3}$
with $\sigma_{\text{local}} = 35.4 \text{ Pa}$		
	$w = 30 \mu\text{m}$	
1.00	$1.1 \times 10^{-2} \pm 1.3 \times 10^{-4}$	$3.7 \times 10^{-2} \pm 2.3 \times 10^{-3}$
with $\sigma_{\text{local}} = 30.2 \text{ Pa}$		
0.50	$4.6 \times 10^{-3} \pm 7.7 \times 10^{-5}$	$2.8 \times 10^{-2} \pm 1.3 \times 10^{-3}$
with $\sigma_{\text{local}} = 26.1 \text{ Pa}$		
0.25	$2.1 \times 10^{-3} \pm 8.6 \times 10^{-5}$	$1.9 \times 10^{-2} \pm 1.2 \times 10^{-4}$
with $\sigma_{\text{local}} = 23.2 \text{ Pa}$		

The pertinent question with regard to rheology is then at what degree of confinement these effects appear. Previous works show that cooperative effects appear at gaps even 250 times larger than the particle size; however, these works have always concerned experimental situations with a certain amount of wall slip [7,14,21], as shown in Table III; the authors of the works shown in Table III explicitly state that wall slip was present in all cases, but in some cases the values of the slip velocities were not reported. The results shown in Table III suggest that the two effects that we consider here are usually strongly coupled. For example, gap-dependent viscosity can also be due to a combination of cooperative effects and wall slip.

Wall slip is determined by the roughness of the shearing surfaces; therefore, we can argue that ξ is highly influenced by the roughness of the shearing surfaces. To demonstrate this, we silanized glass surfaces with a fluorinated silane (Dynasylan®F8261 from Degussa), following the silanization procedure previously described. After treatment with the fluorinated silane, glass slides were immersed in ethanol (from Sigma Aldrich) and left to dry at 20 °C. The solid/liquid/air contact angle of the treated surfaces with the continuous phase and with the oil is $\theta \approx 66 \pm 5^\circ$ and $\theta \approx 55 \pm 1^\circ$, respectively; this shows that, in this case, the surface is less hydrophobic.

By comparing the contact angles of glass surfaces treated with hydrogenated silane, fluorinated silane, and cleaned with piranha solution, we can conclude that when the glass surfaces are more hydrophobic, more oil droplets stick to the glass surface, leading to a suppression of wall slip. The inset in Fig. 5 is an X-Y microscopic image of a glass surface treated with a fluorinated silane, which shows that fewer oil droplets stick to the glass surface, leading to a more inhomogeneous surface. Additionally, we have observed that larger oil droplets slide on the glass surface rather than sticking to it.

We obtained velocity profiles using the shearing surfaces treated with the fluorinated silane in a CP geometry, with a cone having a 6 mm radius and 2° at $w = 80 \mu\text{m}$ and in the presence of partial wall slip, as shown in Fig. 5.

Partial wall slip is defined as a velocity profile that has a gradient but does not extrapolate to zero; at the same imposed shear rates (0.5 and 1 s^{-1}), when “total” wall slip is present, the material moves like a solid block at the speed of the upper cone, as shown in Fig. 2(c). The emulsion used to obtain the velocity profiles shown in Fig. 5 is the same as that used to obtain the velocity profiles shown in Figs. 4 and 3.

These results confirm that the cooperativity length scale is microscopic, on a length scale comparable to the size of the emulsion droplets. The local study of the wall slip by changing the boundary condition shows that the relevant length scale for slip is also the emulsion drop size.

Our results then confirm that ξ is influenced by the boundary conditions [21]. In the absence of wall slip and for our highly jammed and confined system, ξ is of the order of the diameter of one drop (Fig. 5), in agreement with recent simulations [23]. Conversely, if wall slip and cooperative effects are present (Fig. 5), ξ is found to be larger for the same material ($\xi \approx 12 \mu\text{m}$), due to the inhomogeneous stress field induced by the presence of partial slip [24]. In addition, Fig. 5 shows that in this case, we observe nonlocal effects in a geometry that has

TABLE III. Comparison of different characteristic lengths (ξ) used for applying the fluidity model.

System	Gap (μm)	Surface	V_s	ξ (μm)
Emulsion with drop diameter = $6.5 \mu\text{m}$ [7,14]	$\phi = 0.85$ Polydispersity = 20%	Rough	Not reported	32
	$\phi = 0.85$ Polydispersity = 36%			18
	$\phi = 0.80$ Polydispersity = 20%			25
	$\phi = 0.80$ Polydispersity = 36%			16
	$\phi = 0.75$ Polydispersity = 36%			12.5
	$\phi = 0.70$ Polydispersity = 36%			11
	$\phi = 0.66$ Polydispersity = 20%			2
	$\phi = 0.75$ Polydispersity = 20%			22.5
	Emulsion with drop diameter $\approx 3 \mu\text{m}$ [21]	Weakly adhering smooth surface	Not reported	55

a nearly uniform stress and thus should not have those effects. This suggest that, at least in the absence of wall slip, ξ can be understood in terms of a homogeneous roughness induced by the adsorbed oil droplets on the wall. However, as Fig. 5 also shows, there is still a small amount of wall slip present in the sense that the velocity profiles do not exactly extrapolate to zero. This clearly makes it difficult to disentangle wall slip and fluidity effects. Since the velocity profiles are necessarily

averaged over a certain surface area, this may even imply that different near-wall regions with locally varying surface roughnesses have a slightly different interaction with the flow.

In conclusion, we show that by changing the surface chemistry, i.e., the wettability, we change the roughness of the shearing surfaces. If the surface chemistry is such that drops of oil adhere onto the surface, the attached drops generate a roughness that is exactly on the scale of the drops. This is known to be the most effective way of preventing slip; in experiments on granular materials, a layer of the same grains is usually glued onto the surface, similarly to what happens here with the wall. Therefore, by changing the surface chemistry, wall slip can be controlled due to the formation of a “self-generated roughness” induced by the preferential wettability of the disperse phase with the solid surface. The cooperative effects due to confinement appear only below a critical width, which for our emulsion is a diameter of about ten droplets. In the absence of wall slip and for highly confined systems, the viscosity varies over a characteristic length scale ξ , which for our emulsion is of the order of the diameter of one drop. This implies that the observed effects might be due to the fluid elements or droplets that “bump” into the roughness of the wall, and the effect of the wall extends over the distance ξ , implying that ξ can be understood in terms of roughness induced by the adsorbed oil droplets on the wall. We also succeed, in some but not all cases, in disentangling the effect of wall slip and confinement on obtaining gap-dependent viscosities by changing the wettability of the shearing surfaces. Finally, “cooperative effects” can be translated into an effective slip velocity. These results provide a better understanding of the origin of apparent wall slip, which is of major importance for both fundamental material studies and industrial processes in which complex flows play a role.

FIG. 5. Velocity profiles obtained in a CP geometry using a partially hydrophobic surface as plate at a radial position equivalent to a gap of $80 \mu\text{m}$. Imposed shear rates 0.5 and 1 s^{-1} (bottom to top). The gray lines are the fittings of the velocity profiles to the fluidity model with a characteristic length scale $\xi \approx 12 \mu\text{m}$. Inset: microscopic image showing that only a few droplets of the flowing emulsion stick to the partially hydrophobic surface; the white bar is $10 \mu\text{m}$.

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