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Channel flow in a Langmuir monolayer: Unusual velocity profiles in a liquid-crystalline mesophase

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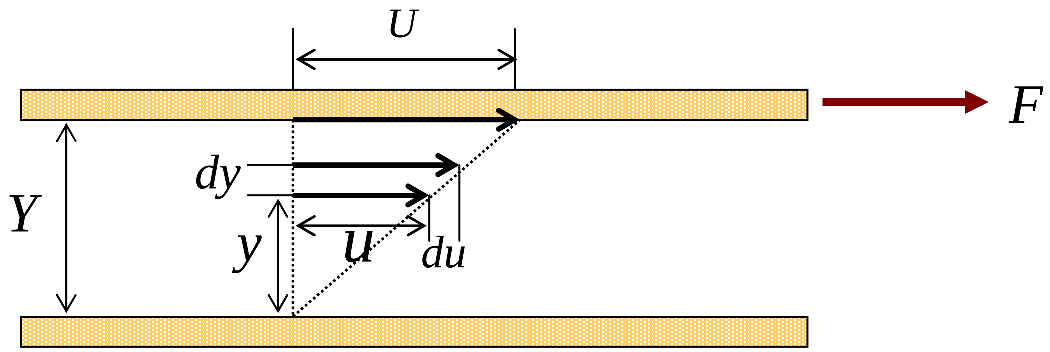
1/18/08

Abstract

We have observed the surface-pressure driven flow of an arachidic (eicosanoic) acid Langmuir monolayer through a narrow channel using Brewster angle microscopy. By following distinctive features of the monolayer domain morphology we determined the velocity profile across the channel for various values of surface pressure over a wide range of flow rates. At low surface pressure within the L_2 mesophase, the velocity profile is parabolic for low flow rates. This implies that the surface viscosity dominates the coupling to the aqueous subphase as a source of dissipation and that the monolayer behaves as a Newtonian fluid. At extremely high shear rates, a flattened velocity profile is observed, similar to plug flow. At higher surface pressure ($\geqslant 20$ mN/m) the velocity profile is again parabolic for low flow rates. However, as the flow rate is increased the velocity profile is observed to gradually sharpen, eventually becoming triangular. The critical shear rate for the onset of this flow profile is 0.2 s^{-1}. In a typical fluid, such a profile would indicate shear thickening. However, measurement of the surface pressure drop along the channel versus flow rate indicates that macroscopic surface viscosity actually decreases with shear rate in this regime. The sharp change in interfacial rheology at $\pi = 20$ mN/m suggests the presence of a monolayer phase transition. [S1063-651X(97)14409-9]

Newton's equation of viscosity - textbook



At fluid mechanics with engineering applications

Resisting Force

$$F \sim \frac{AU}{Y}$$

Shear stress (Newton's equation of viscosity)

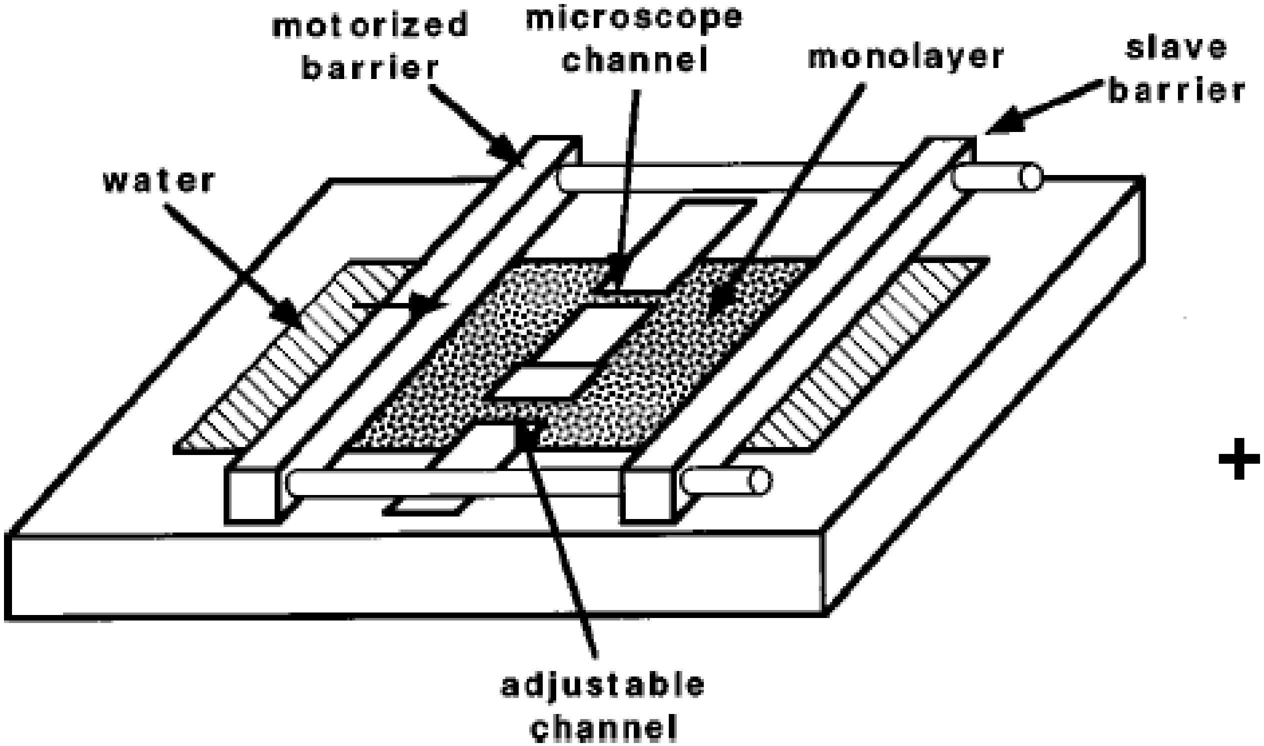
$$\tau = \frac{F}{A} = \mu \frac{U}{Y} = \mu \frac{du}{dy}$$

Shear *Rate*

Coefficient of viscosity

$$\mu = \frac{\tau}{du/dy}$$

Setup



+ **BAM**

Channel length 25mm, width 1mm

Sample $CH_3(CH_2)_{18}COOH$

Brewster Angle Microscopy - image

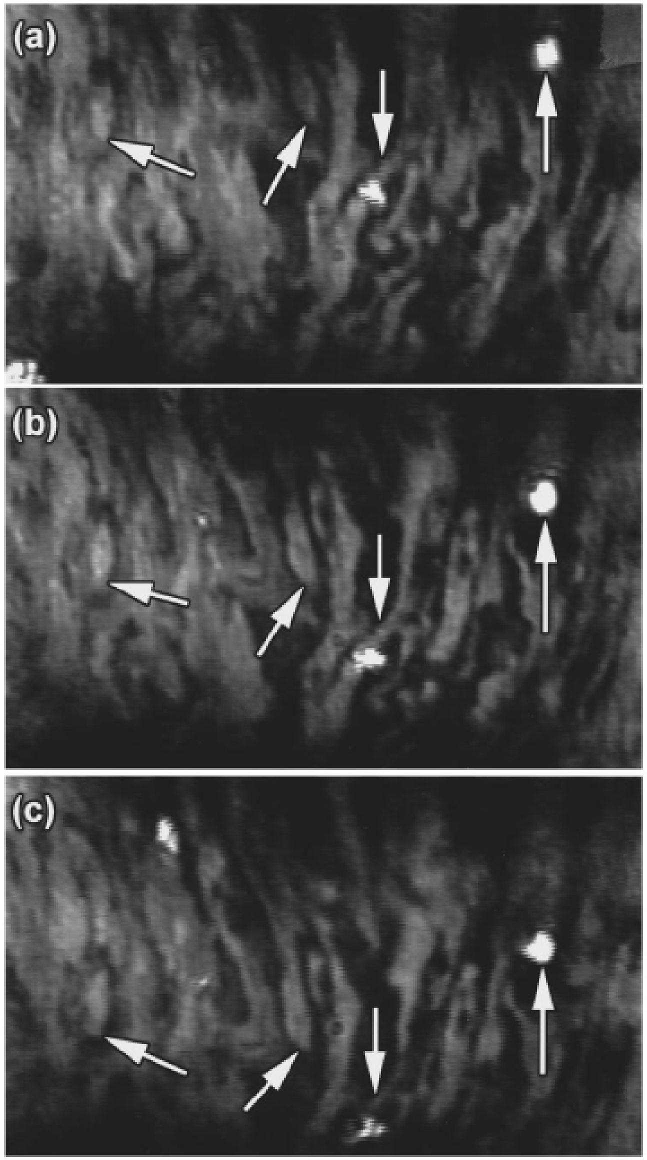


FIG. 2. (a)–(c) A typical sequence of BAM images during arachidic acid monolayer flow from top to bottom. Distinctive features of the domain boundaries (some examples are indicated by arrows) are followed frame-by-frame in order to generate the velocity profile across the channel.

Result - surface pressure at ~18.0 (mN/m)

Low flow rate fitting eq. – Laminar flow

At fluid mechanics with engineering applications

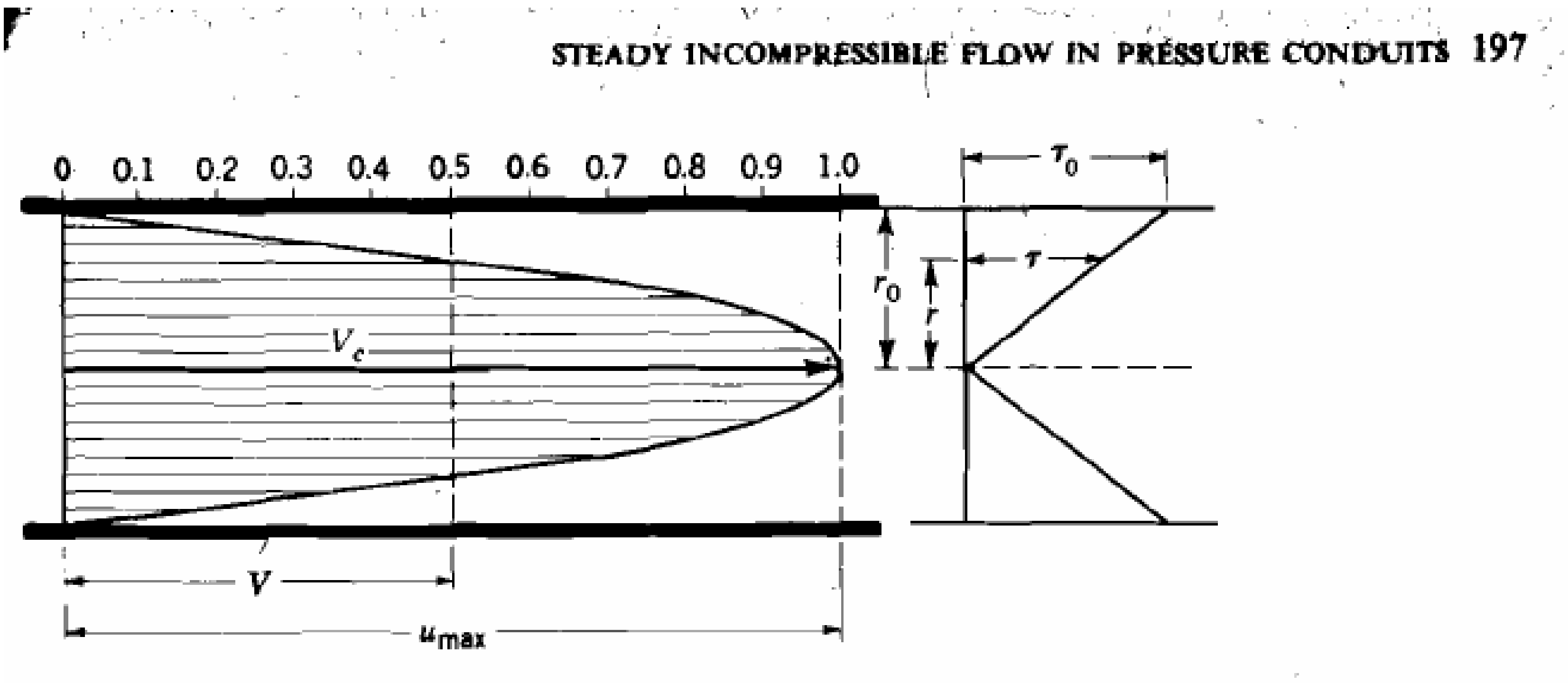


Figure 8.3. Velocity profile in laminar flow and distribution of shear stress.

Low flow rate fitting eq.

$$u = u_{\max} - \frac{h_L \gamma}{4 \mu L} r^2$$

Result - surface pressure at ~18.0 (mN/m)

Parabolic (Poiseuille) profile : Newtonian fluid – low flow rate

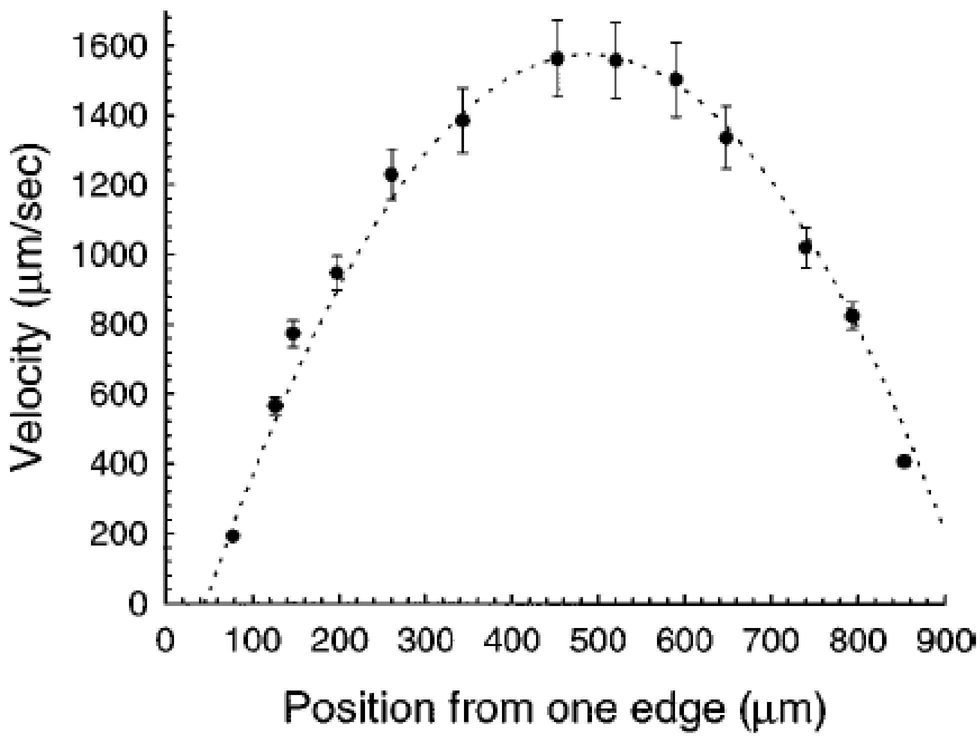


FIG. 3. Velocity profile during monolayer flow at $\pi = 18.0$ mN/m ($T = 21.5$ °C). The dashed line in this figure (and all other figures) represents the best parabolic fit to the data. The parabolic (Poiseuille) profile indicates that the interfacial viscosity dominates the drag due to subphase coupling and that the monolayer response is Newtonian.

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↓

$$\mu_s > a\mu$$

Channel width $2a$

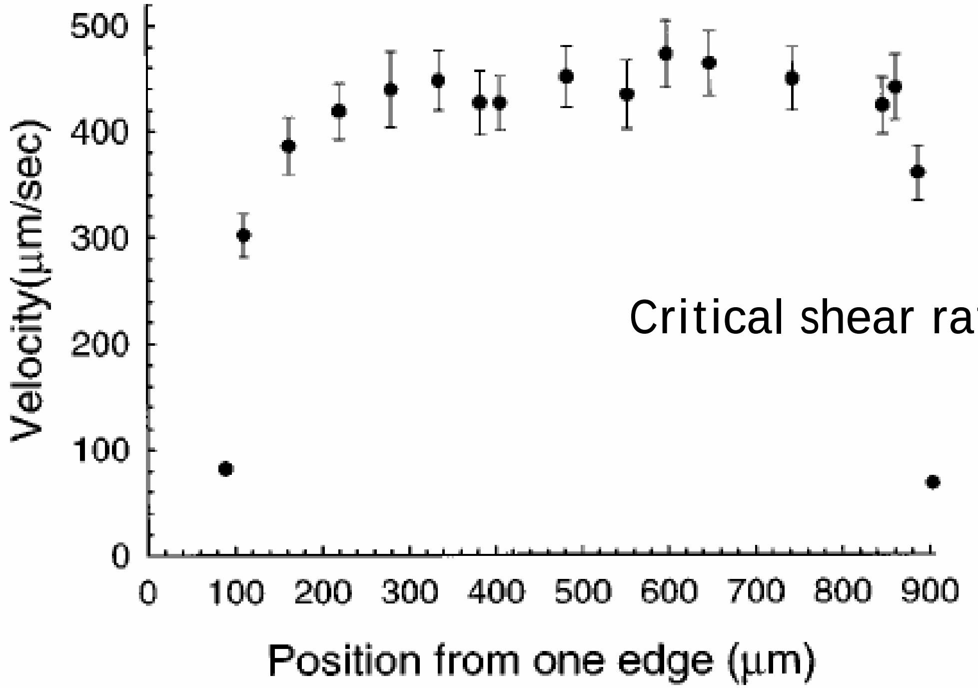
↓

$$\mu_s > 5\times10^{-4}\, g/s$$

In this paper $10^{-3} \sim 10^{-2}$

Result - surface pressure at ~18.0 (mN/m)

Shear thinning (pseudoplastic) profile : NON-Newtonian fluid – high flow rate

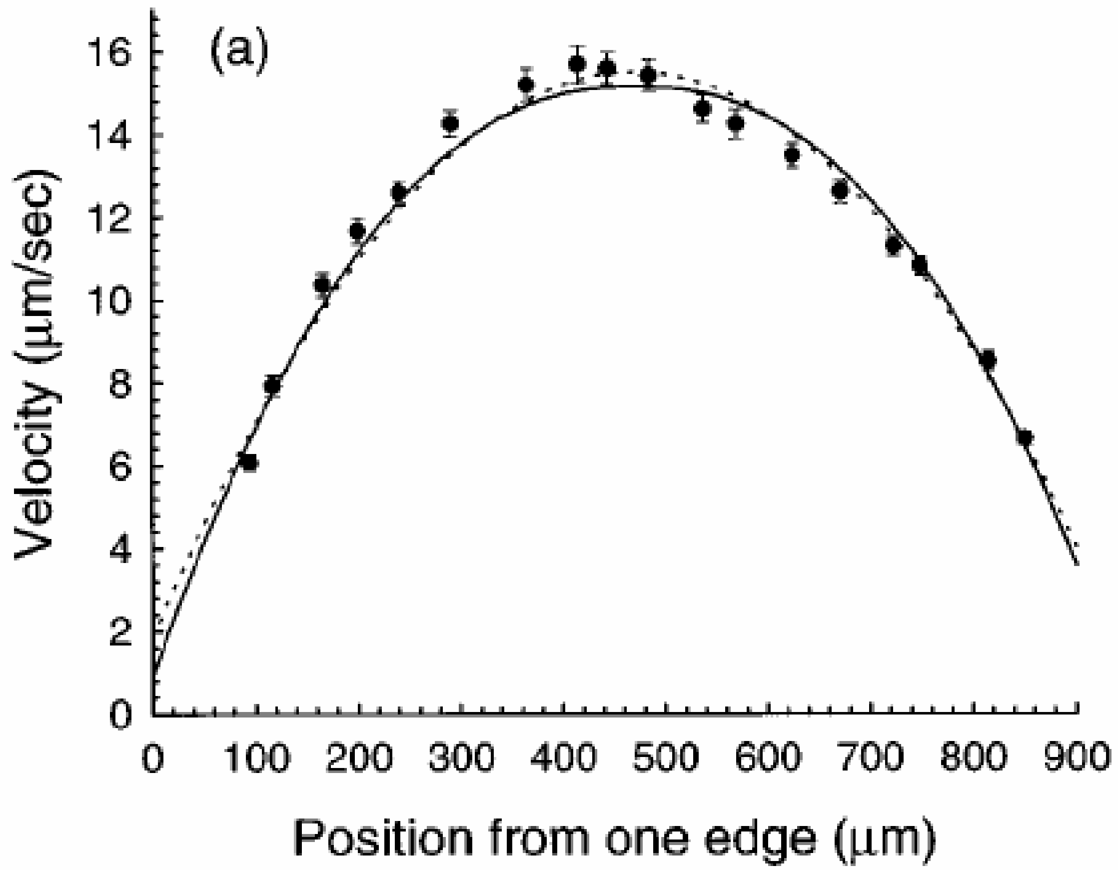


Critical shear rate (plug flow) : 5 s^{-1}

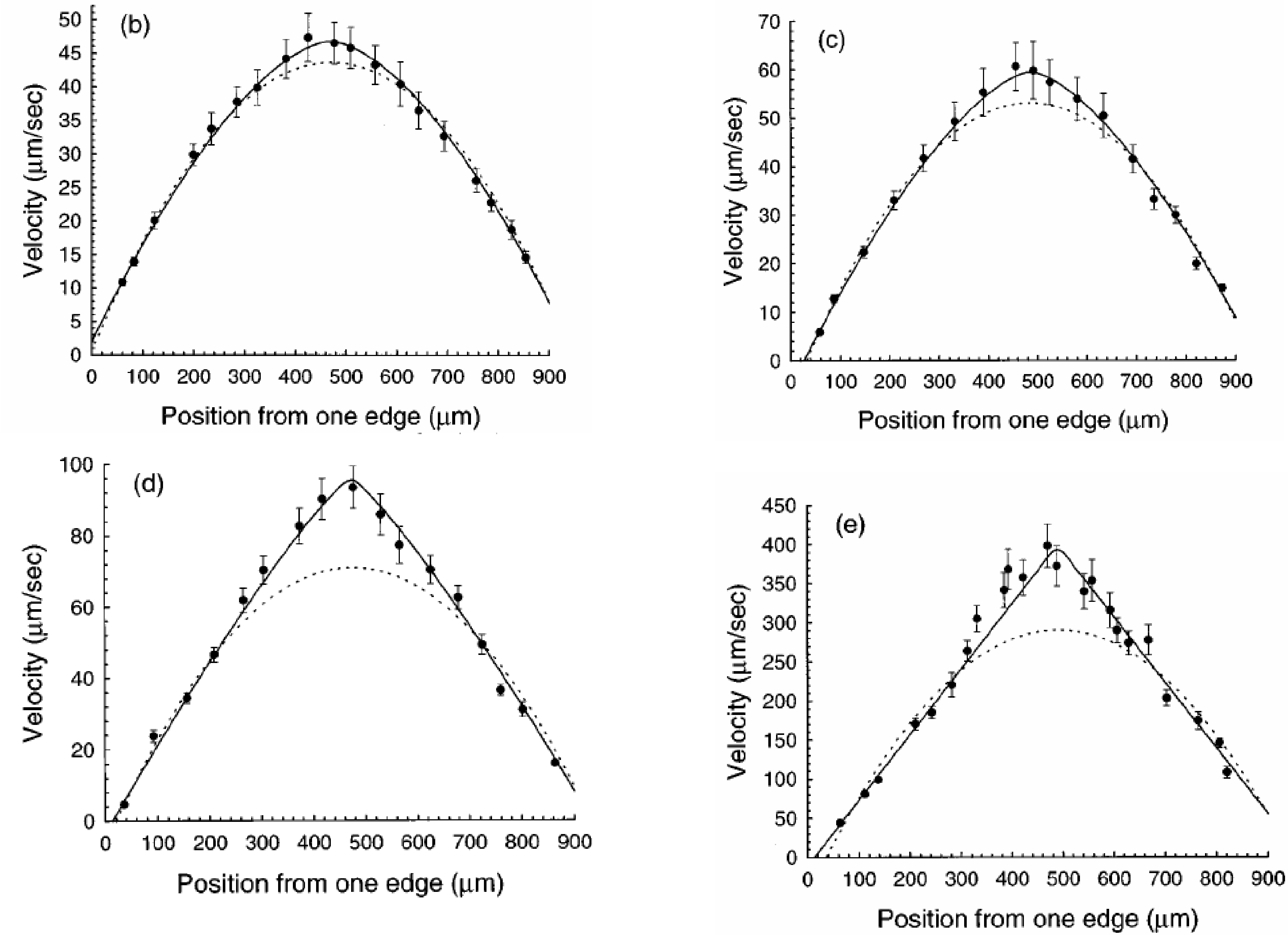
FIG. 4. Velocity profile during monolayer flow at $\pi = 12.5$ mN/m ($T = 21.5\ ^\circ$C). The trapezoidal profile (plug flow) indicates shear-thinning response—the shear is confined to narrow layers near the edges. The profile at lower flow rates is similar to the parabolic one shown in Fig. 3.

Result - surface pressure at > 20.0 (mN/m)

Low flow rate



Result - surface pressure at > 20.0 (mN/m)



Result - surface pressure at > 20.0 (mN/m)

Non-Newtonian fluids [Power-raw model]

$$\tau = K\left|\frac{du}{dx}\right|^{\alpha-1}\frac{du}{dx}$$

τ Shear stress K constant du/dx Shear rate

Viscosity

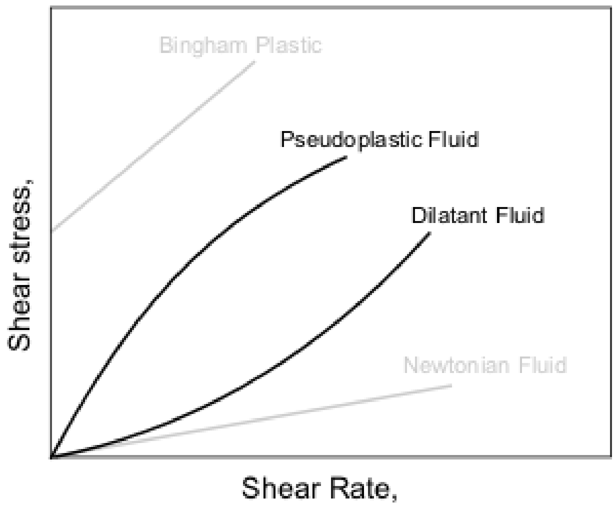
$$\mu_{app} = K\left|\frac{du}{dx}\right|^{\alpha-1}$$

$\alpha < 1$ Pseudoplastic (shear-thinning)

$\alpha > 1$ Dilatant (shear-thickening)

$\alpha = 1$ Newtonian model

Wikipedia



Result - surface pressure at > 20.0 (mN/m)

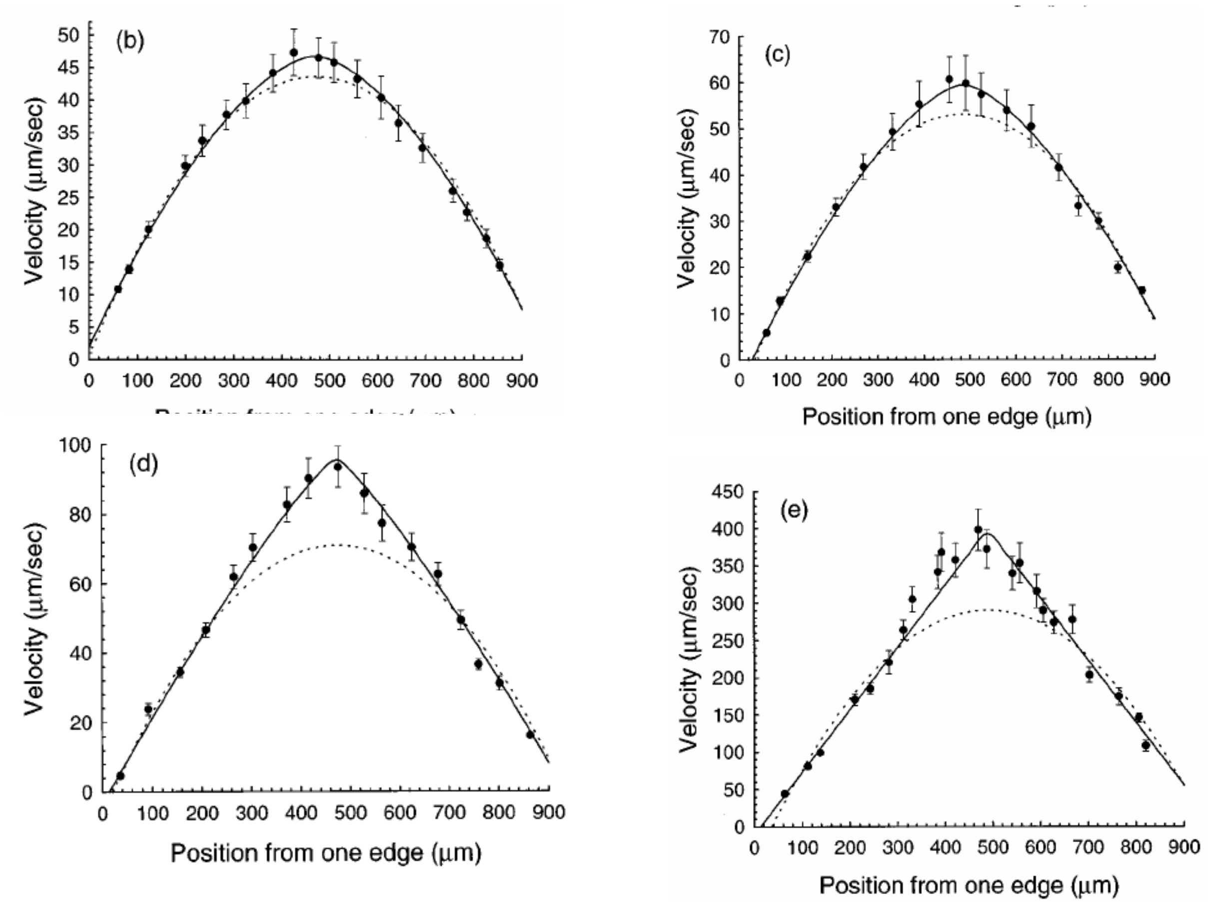


FIG. 5. Velocity profiles during monolayer flow at $\pi = 20.5$ mN/m ($T = 21.5$ °C) as the flow rate is increased. The dashed lines represent the best parabolic fit and the solid lines represent the best fit to a power law model (see text). (a) At low flow rates the profile is effectively parabolic, consistent with Newtonian response. (b)–(d) As the flow rate is increased the profile becomes sharper. The exponents α for the power law fits are as follows: (a) 0.77 (± 0.14), (b) 1.56 (± 0.12), (c) 1.9 (± 0.5), (d) 9 ($-6, +\infty$), (e) 182 ($-171, +\infty$).

Result - surface pressure at > 20.0 (mN/m)

Non-Newtonian fluids [*ad hoc* Power-raw model] in paper

$$u \sim \left[1 - \left(\frac{x}{a}\right)^{(1+\alpha)/\alpha} \right]$$ a half-width of channel $x = 0$ centerline center

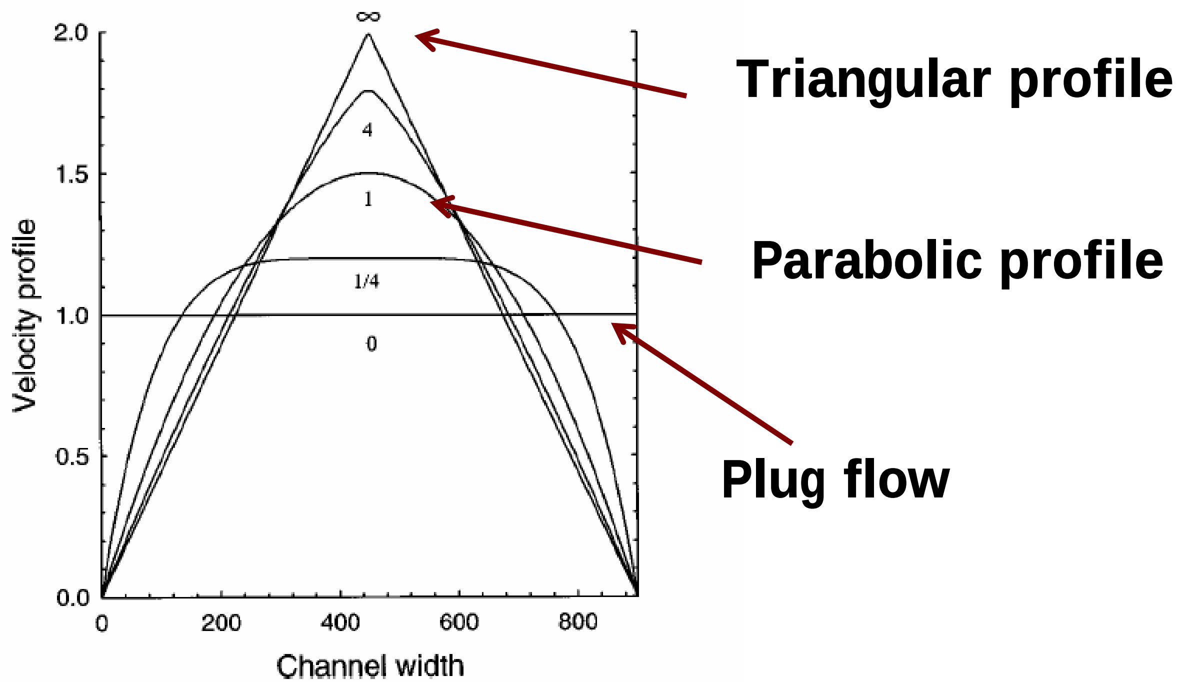


FIG. 6. Theoretical velocity profiles obtained using the *ad hoc* power law model. For an exponent, α, of unity, the model reduces to a Newtonian fluid, yielding a parabolic profile. For exponents less than unity (shear-thinning), the profile flattens out, approaching plug flow at $\alpha = 0$. For exponents greater than unity (shear-thickening), the profile becomes sharper approaching a triangle at $\alpha = \infty$.

Result - surface pressure at > 20.0 (mN/m)

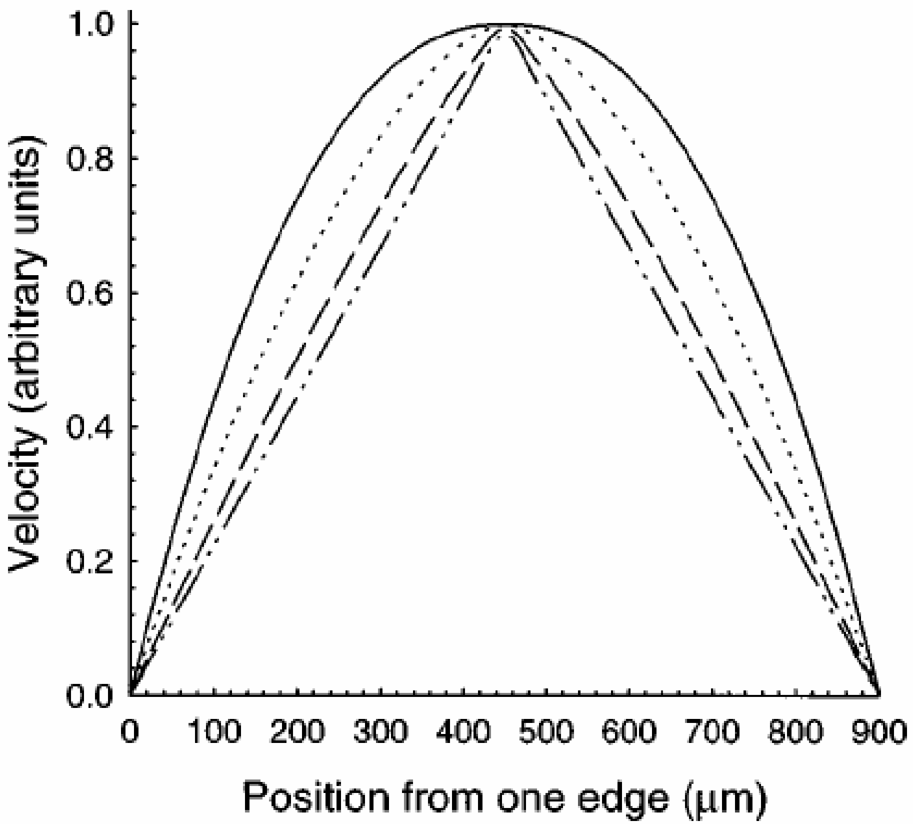


FIG. 7. Evolution of the measured velocity profiles for a monolayer at $\pi = 20.5$ mN/m with increasing flow rate. The fits are scaled to have the same maximum and plotted without data points for clarity. The actual maximum velocities are as follows: solid line, 15.2 μm/s; dotted line, 46.8 μm/s; dashed line, 95.7 μm/s; and dash-dotted line, 398.3 μm/s.