Magnetic Needle Viscometer for Langmuir Monolayers

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We have built a magnetic needle viscometer capable of measuring the surface shear viscosity of Langmuir monolayers at constant surface pressure or molecular area. A Langmuir trough with dual symmetrical compression/expansion barriers is positioned between two electromagnetic coils that create a homogeneous magnetic field gradient. The gradient drives a Teflon-encapsulated magnetic needle floating on the monolayer along the surface to a terminal velocity. A channel created by two glass plates centers the needle and minimizes drift. The ratio of monolayer surface shear viscosity at a given composition, temperature, surface pressure, and so forth to a reference surface shear viscosity is determined by taking the appropriate ratio of the limiting velocities of the magnetic needle for a given applied force. The monolayer viscometer was calibrated using thin films of silicone oil of known viscosity. We demonstrate the utility of the viscometer by showing that the shear viscosity of saturated dipalmitoylphosphatidylcholine is strongly dependent on temperature and surface pressure and correlates with the liquid expanded to liquid condensed phase transition.

Introduction

The study of the viscosity and flow behavior of Langmuir monolayers has a long history as monolayer rheology plays a crucial role in dynamic processes at gas–liquid interfaces. There are two broad categories of surface viscosity measuring devices. The first is based on measuring the response of a monolayer to a torsion pendulum or other oscillator. The second category, typified by the canal viscometer, relies on measuring aspects of a surface pressure gradient induced flow; the surface shear viscosity is evaluated by comparing the flow to solutions of the Navier–Stokes equation that are appropriate to the geometry. For these types of viscometers, it is often necessary to determine the flow profile of the monolayer, using tracer particles, fluorescence microscopy, or Brewster angle microscopy. The variation in surface pressure in the canal viscometer also makes it difficult to assign a particular surface pressure to a given surface viscosity, especially at phase coexistence where large variations in monolayer morphology occur over small changes in surface pressure. The magnetic needle viscometer, first developed by Shahin and recently modified by Brooks et al., is a relatively new method for measuring monolayer viscosity. Helmholtz coils with a controlled current apply an oscillating force to a magnetic needle floating on the monolayer, which drives the needle into oscillation. The complex shear modulus is determined from measurements of the in-phase and out-of-phase response of the resulting strain. We report the design of a simplified magnetic needle viscometer capable of quick, reliable measurements of the steady surface shear viscosity at constant surface pressure. Instead of an oscillating force, we apply a constant force to the magnetic needle and extract the shear surface viscosity of the monolayer from the terminal velocity of the needle. Thin films of silicone oils of known viscosity are used to calibrate the viscometer. We have used the viscometer to determine the steady surface shear viscosity of dipalmitoylphosphatidylcholine (DPPC) at 20, 25, 30, and 37 °C over a range of surface pressures. The strong surface pressure dependence of the viscosity of DPPC, especially at liquid expanded—liquid condensed phase coexistence, illustrates the benefits of this viscometer over the more commonly used channel viscometers that by necessity require surface tension gradients.

DPPC is a major component (50–75% by mass) of human and mammalian lung surfactant (LS), in addition to being common to many biological membranes. The optimal composition of replacement lung surfactants is still an open question as the physiological consequences of monolayer physical properties that depend on composition, such as viscosity, phase coexistence, collapse pressure,
and resspreading.\textsuperscript{13,15} are not well understood. In addition to its role in lowering the work of breathing, lung surfactant protects the lungs from particulate and other foreign matter by inducing surface tension gradient driven flows from the alveoli. The surface shear viscosity is likely a determining factor in these flows of contaminants.\textsuperscript{16}

**Apparatus**

**Langmuir Trough.** Figure 1 shows the Langmuir trough, which was machined from virgin Teflon and attached to a copper plate for fast and uniform heat conduction. A recess 15 cm long, 2.5 cm wide, and 2.5 cm deep is centered across the midline of the trough. The recess is designed to hold two Teflon spacers with adjustable slots that in turn hold two hydrophilic glass plates positioned in two Teflon slots to make a channel. The plates are parallel with an adjustable width. (E) Wilhelmy plate surface pressure sensor. (F) Thermistor for temperature measurement. (G) Thermoelectric coolers (TEC) sandwiched between a copper plate attached to the Teflon trough and a polysulfone water cell (J) for recirculating cooling water. (H) Stepper motor connected to a left-right lead screw. (I) Hard-limit switch for motor control. The whole trough is mounted on an adjustable lab-jack and fixed to a vibration-free table.

**Figure 1.** Photograph of Langmuir trough/surface viscometer. (A) Dual Teflon barriers, instead of the flat barrier in most commercial troughs; the barriers are notched to minimize leakage at high surface pressure. (B) Springs keep the Teflon barrier in position and provide tight contact with the trough. (C) Teflon trough with effective area of 260 cm\(^2\). (D) Two hydrophilic glass plates positioned in two Teflon slots to make a channel. The plates are parallel with an adjustable width. (E) Wilhelmy plate surface pressure sensor. (F) Thermistor for temperature measurement. (G) Thermoelectric coolers (TEC) sandwiched between a copper plate attached to the Teflon trough and a polysulfone water cell (J) for recirculating cooling water. (H) Stepper motor connected to a left-right lead screw. (I) Hard-limit switch for motor control. The whole trough is mounted on an adjustable lab-jack and fixed to a vibration-free table.

**Figure 2.** A schematic top-view diagram of the magnetic needle viscometer. Two electromagnetic coils 61 cm in diameter were set 61 cm apart to provide a uniform magnetic field gradient. The Langmuir trough with dual symmetrical barriers was offset between the two electromagnetic coils so that the needle channel was along the axis of the coils in the most uniform portion of the magnetic field gradient (Figure 4). Two parallel glass plates created an open-ended channel to guide the direction of the magnetic needle and determine the boundayary conditions for the flow. A small glass plate was placed near the end of each channel to prevent the needle from sticking to the end of the channel.

There was no variation in surface pressure measured over the length of the channel.

The needle is assembled from a 1.5 mm diameter \(\times\) 8 mm long magnetic stirring bar (Fisher Scientific) centered in the middle of a 3.0 cm long hollow Teflon tube (McMaster-Carr, Los Angeles, CA) with an outside diameter of 2 mm. A small length (about 5 mm) of black heat shrink Teflon tubing is also placed in the tube to provide added contrast in the video images. The ends of the tube are sealed with small plug cuts from a Teflon sheet. The mass of the needle assembly is about 200 mg, making the net density of the needle about 2.2 g/cm\(^3\). Most of the mass of the assembly is concentrated in the magnet; the magnetic moment of the needle is proportional to the mass of the magnet, so a smaller magnet means a smaller net force on the needle (eq 3). Although the density of the needle is significantly greater than that of water, the needle does not sink up to a surface pressure of 45–50 mN/m, due to the added buoyancy provided by surface tension. This particular assembly is a compromise to allow investigation of viscous monolayers over a wide range of surface pressures, while keeping the needle assembly short enough to easily allow steady-state conditions to be reached in the channel. Typical needle speeds during measurements ranged from 0 to 1.5 cm/s.

The water surface in the channel formed by the glass plates is centered along the axis of the magnetic field gradient, which is generated by applying equal and oppositely directed current to two 61 cm diameter coils, separated by 61 cm, located on either side of the trough (see Figure 2). Each electromagnetic coil was made by putting 100 turns of 18 AWG magnetic wire (McMaster-Carr, Los Angeles, CA) on a wooden spool 61 cm in diameter. The resistance for each coil at room temperature is around 2.2 \(\Omega\). The force on the magnetic needle is the product of the magnetic dipole moment of the needle and the magnetic field gradient generated by the coils (see eq 3). The trough was placed between the coils so that the center of the needle channel was displaced 18 cm horizontally from one of the coils to take advantage of the most uniform part of the magnetic field gradient, which varies by <1% over...
the length of the channel (see figures 3 and 4). Two power supplies control current to the coils to adjust the magnitude of the magnetic field gradient (EXH 30-10, Electronic Measurements, Inc., NJ). Above the channel, a video camera (Sony CCD-TR940) records the needle speed. The video signal is digitized (ST3155, Data Translations, Inc.) to determine the needle velocity.

The surface pressure and area per molecule in the trough are controlled via two Teflon barriers driven by a stepper motor (M062-LS09, Velmex Inc., Bloomfield, NY) via a left-right lead screw (MB2518CJ-S2.5(2), Velmex Inc.), which creates a symmetric compression and expansion. To reduce monolayer leakage, the body of each barrier extends down into the trough well and is pulled tightly down onto the trough sides by four springs. A Wilhelmy type pressure sensor (R&K, Germany) is positioned near the glass plates to measure the surface pressure. The trough temperature can be controlled between 10 and 45 °C via 12 thermoelectric coolers (DT12-6-01LS, Marlow Industries, Inc., Dallas, TX) positioned between the copper plates and a polysulfone water cell. One thermistor (44030, Omega) was fixed to one of the barriers to measure the trough temperature. The whole trough was mounted on an adjustable lab-jack (Thorslab) and fixed to a vibration-free table (RS 3000, Newport, Irvine, CA).

**Figure 3.** Schematic of two electromagnetic coils of radius R, separated by a distance L. The magnetic field and gradient at the point P located a distance x from coil A are given by eqs 1–3. B is the net magnetic field created by both electromagnetic coils.

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**Figure 3.** Schematic of two electromagnetic coils of radius R, separated by a distance L. The magnetic field and gradient at the point P located a distance x from coil A are given by eqs 1–3. B is the net magnetic field created by both electromagnetic coils.

**Figure 4.** Comparison of the calculated magnetic field and calculated magnetic field gradient as a function of the distance between the two electromagnetic coils for different coil/current configurations. (A) shows the calculated magnetic field and magnetic field gradient for the typical Helmholtz setting (L = R in Figure 3) in which the distance between the two coils equals the radius of the coil. The red lines show the magnetic field and gradient when the current is equal and in the same direction (Iₐ = I₉). The green lines show the field and gradient for the same separation, but with Iₐ = I₉. (B) shows the calculated magnetic field and magnetic field gradient for the configuration used in these experiments, with the distance between the two coils equal to the diameter of the coils (L = 2R in Figure 3) and equal but oppositely directed current applied to the coils (Iₐ = −I₉). This configuration gives a strong and uniform magnetic field gradient.

The force on a magnet in a magnetic field is proportional to the gradient of the field:

\[
F_m = \eta \left( \frac{dB}{dx} \right) = \frac{3\mu_0 N R^3}{2} \left[ \frac{x}{(R^2 + x^2)^{5/2}} - \frac{(L - x) R}{(R^2 + (L - x)^2)^{5/2}} \right] 
\]

\( \eta \) is the magnetic dipole moment of the needle. For our purposes, a homogeneous magnetic field gradient is more important than a homogeneous magnetic field. The typical design of Helmholtz coils (Iₐ = I₉, L = R, see figure 4a) creates a homogeneous magnetic field but does not provide a homogeneous magnetic field gradient; in fact, the gradient is zero at the midpoint between the two coils (x = R/2). However, a constant applied force can be achieved by setting the distance between the coils equal to twice the coil radius, L = 2R, and making Iₐ = −I₉, that is, applying the same current to each coil but in opposite directions (Figure 4b). Figure 4 shows that for L = 2R and Iₐ = −I₉ the calculated magnetic field is constantly decreasing and a homogeneous magnetic field gradient.
Figure 5. The control diagram for the magnetic needle viscometer. The arrows show the directions of signals. The host computer uses an IBM-compatible personal computer with an Intel Pentium II 350 CPU and Microsoft Windows 95 operating system. There are three plug-in boards and one built-in serial communication port to exchange signal and data between the host computer and the magnetic needle viscometer.

exists between much of the coils. The magnetic field direction changes at the midpoint between the two coils; therefore, the center of the needle channel was displaced 18 cm horizontally from one of the coils. This centers the channel in the most homogeneous portion of the magnetic field gradient. An equally constant applied force can be made by setting \( I_A = 2I_B \) and \( L = R \) (Figure 4A); however, for a given magnetic needle, the maximum force is less than half that used in these experiments.

**Control and Software.** The viscometer was controlled by an IBM-compatible computer with an Intel Pentium II 350 processor operating Windows 95 using a control algorithm written in Visual C++ (Microsoft Visual C++, version 6.0). Figure 5 shows the control diagram of data input and output. Three plug-in computer boards and one built-in serial communication port were used for communication between the host computer and the magnetic needle viscometer. The serial communication port is configured for communication between the host computer and the stepper motor controller (NF90, Velmex Inc.). This system controls the movement of the stepper motor for the two barriers and determines the barrier position, from which the monolayer area is calculated. An analog-to-digital board (CIO-DAS802/16, Computer Boards Inc., www.computerboards.com) translates the analog signals from the Wilhelmy plate which gives the surface pressure and converts thermistor resistance into temperature via a custom algorithm. A digital-to-analog board (CIO-DDA06) is used to control the power supply (DCS-60-18, Sorensen, San Diego, CA) for the thermoelectric coolers, based on the feedback from the thermistor using a PID algorithm. The same board controls the two power supplies for the two electromagnetic coils and a custom relay that controls the direction and magnitude of the current to the two electromagnetic coils. A video board (DT-ST3155, Data Translations Inc., www.datx.com) was used to digitize the video images to the host computer in real time. To obtain the real-time needle speed, the digital signal from the video camera is reduced to black and white according to a certain threshold so that the position of the needle can be extracted from the video signal. A monitor window shows information of all signals from the viscometer, and an isotherm window records the isotherms. Time, pressure, molecular area, power for both coils, and needle speed were stored in data files for later processing. A similar program for Nima Langmuir troughs can be found at www.chemengr.ucsb.edu/~ceweb/faculty/zasadzinski/nima.

**Experimental Section**

**Materials.** 1,2-Dipalmitoyl-sn-glycero-3-phosphatidylcholine (DPPC) was purchased from Avanti Polar Lipids (Alabaster, AL; purity > 99%) and used without further purification. A DPPC spreading solution was prepared by mixing chloroform with powdered DPPC at 0.5 mg/mL with pure chloroform (Aldrich, St. Louis, MO). The lipid mixtures for fluorescence imaging are doped with 0.5 mol % of the fluorescent lipid Texas Red-DHPE (Molecular Probes). Silicone oil viscosity standards 100 (actual viscosity is 97.5 cP at 25 °C) and 1000 (980 cP at 25 °C) from Brookfield Engineering Laboratories, Inc. (Middleboro, MA) were used as received. Water was prepared using a Millipore Milli-Q system and had a resistivity of > 18 MΩ cm. For imaging, a custom fluorescence microscope/Langmuir trough system was used.13,14 Images were recorded by a JVC super VHS VCR and digitized via a Scion frame grabber. The resulting digitized images are processed and analyzed following a custom-designed protocol.13

**Data Processing and Calibration**

**From Terminal Velocity to Viscosity.** For a given applied force, \( F \), the terminal velocity, \( v_T \), of the magnetic needle on the monolayer-covered interface is set by the sum of the viscous drag on the needle from the bulk subphase and from the monolayer:

\[
F = \left( \frac{\mu_P c}{L''} + \frac{\mu_c a_s}{L''} \right) v_1
\]

(4)

\( P_c \) is the contact perimeter between the needle and the monolayer; \( a_s \) is the contact area between the needle and the subphase, \( \mu \) is the subphase viscosity, and \( L'' \) and \( L''' \) are the characteristic length scales over which the velocity decays in the surface and the subphase, respectively.11 With no monolayer present, for the same applied force,

\[
F = \frac{\mu a_s v}{L'''}
\]

(5)

with \( v \) being the terminal needle velocity on the bare subphase. To determine \( \mu_a \), we equate eqs 4 and 5, assuming that the subphase drag is independent of the surface pressure (or other monolayer properties):

\[
\frac{\mu a_s v}{L'''} = \left( \frac{\mu_P c}{L''} + \frac{\mu_c a_s}{L''} \right) v_1
\]

(6)

Reorganizing this expression gives the Boussinesq number, \( \text{Bo} \), which is the ratio of surface drag to subphase drag at these conditions:

\[
\frac{v - 1}{v_1} = \frac{\mu P c d / L'''}{\mu a_s / L'''} = \text{Bo}
\]

(7)

When \( \text{Bo} \gg 1 \), the drag on the probe is primarily from the monolayer; when \( \text{Bo} \ll 1 \), the drag is primarily from the subphase. If the surface viscosities, \( \mu_s (\pi_1) \) and \( \mu_s (\pi_2) \), vary at different surface pressures (or any other param-

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eters), two different needle velocities, \( v_1 \) and \( v_2 \), will result from a given \( F \), resulting in \( \text{Bo}(\tau_1) \) and \( \text{Bo}(\tau_2) \). Taking the ratio of the \( \text{Bo} \) gives the ratio of the surface viscosity at the different surface pressures, which allows us to determine the viscosity ratio relative to any reference surface viscosity:

\[
\frac{v_2}{v_1} = \frac{\text{Bo}(\tau_2)}{\text{Bo}(\tau_1)} = \frac{\mu_i(\tau_2)}{\mu_i(\tau_1)}
\]

Calibration. From eq 8, it is clear that to obtain absolute measurements of the viscosity, rather than viscosity ratios, the viscometer must be calibrated against a known set of monolayer viscosities. Thin films of silicone oils were used as a viscosity standard (Brookfield Engineering Laboratories, Inc., Middleboro, MA) to calibrate the viscometer. Two oils were used: 100 (actual viscosity is 97.5 cP) and 1000 (actual viscosity is 980 cP) at 25 °C. A small amount (usually 40 and 60 ± 100 µL, respectively) of the silicon oil was spread on the water subphase surface (≈260 cm²). Silicone oil is insoluble in water and therefore forms a thin film on the top of the water subphase; the two-dimensional viscosity is the product of the bulk viscosity and the thickness of the oil layer. The thickness is equal to the volume of silicone oil deposited divided by the trough area, which can be adjusted from 260 to 60 cm². This gave films ranging from 1.5 to 10 µm thick and shear surface viscosities from 2.2 × 10⁻⁴ to 1.0 × 10⁻² P cm (also known as surface poise, or g s⁻¹). This was sufficient to cover the useful range of the viscometer.

To determine the calibration for the particular needle/through/channel system used, it is necessary to relate the calculated silicone oil surface viscosities to the normalized terminal needle velocities measured for these films. Rewriting eq 8 gives a simple relationship between the measured terminal needle velocity, \( v \), for a given silicon oil thickness with a known surface viscosity, \( \mu_i \), relative to the terminal needle velocity, \( v_i \), and surface viscosity, \( \mu_{sj} \), for a second silicon oil thickness. Again, the terminal needle velocity for each film is normalized to the terminal needle velocity on the bare subphase, \( v \):

\[
\mu_{sj} = \left( \frac{v_i}{v} - 1 \right) \frac{D_i}{D} = \left( \frac{v_i}{v} - 1 \right) \sum_{i=1}^{N} D_i
\]

From this expression, the calibration constant, \( D \), is simply the ratio of the known viscosity of the silicone oil thin film to the normalized terminal needle velocity measured for that particular thin film. As each silicone oil film gives one value of the calibration constant, it is reasonable to take the average over all of the silicone oil films tested:

\[
D = \frac{1}{N} \sum_{i=1}^{N} D_i
\]

Application of the Viscometer to DPPC

DPPC is ubiquitous in cell membranes and is a major component of human lung surfactant. As such, qualitative measures of the viscosity have been reported by several investigators; however, the limited quantitative values are widely varying.20,22,23 This is likely due to the strong temperature and surface pressure dependence of the morphology of DPPC monolayers.20,22,23 At 20 °C, DPPC monolayers have a coexistence between a liquid expanded (LE) and a liquid condensed (LC) phase that begins at a surface pressure of about 8–10 mN/m. The LE phase is disordered and expected to be rather fluid, while the LC phase has a semicrystalline packing with a rectangular unit cell. The area per chain is 23.3 Å², and the molecules are tilted with respect to the normal to the interface.24 As the temperature increases, the surface pressure at which the LE-LC phase transition occurs increases; by 37 °C, the phase transition pressure is above 40 mN/m, near the limit of surface pressure that can be examined with our viscometer before the needle sinks (Figure 7).

Figure 8 shows the normalized speed and calibrated viscosity (from eq 11) for DPPC as a function of surface pressure. The viscosity decreases significantly as the

\[
\mu_{sj} = D \left( \frac{v_i}{v} - 1 \right)
\]
temperature increases; for example, there is almost an order of magnitude difference in surface viscosity at 25 mN/m between 20 and 25 °C, showing the necessity of good temperature control when measuring surface viscosities. At 37 °C, the surface viscosity cannot be resolved with this instrument; essentially all of the drag on the needle is from the subphase rather than from the DPPC monolayer. However, the constant normalized terminal needle velocity at 37 °C (Figure 8A) shows that there is a minimal change in the subphase drag as a function of the surface pressure, which justifies the assumptions inherent in eqs 4–8. At 37 °C, the surface viscosity cannot be resolved with this instrument; essentially all of the drag on the needle is from the subphase rather than from the DPPC monolayer.

For the 20, 25, and 30 °C data, the slopes of the normalized speed and the surface viscosity plots change abruptly at surface pressures that correspond closely to the LE–LC transition pressure at that temperature (Figure 7). The LE–LC transition for DPPC is about 8 mN/m at 20 °C. This LE–LC coexistence pressure increases as the temperature increases: 10–14 mN/m at 25 °C, 20–24 mN/m at 30 °C, and 40–44 mN/m at 37 °C.20,24,25 Our results are consistent with those of Gaub et al., who found that the surface viscosity increased strongly at the LE–LC transition surface pressure.20 In general, the surface viscosity is a significant fraction of the drag on the needle only if the surface pressure is higher than the LE–LC transition.

Figure 7. Fluorescence micrographs of a DPPC monolayer on a pure water subphase. (A) DPPC at a surface pressure of 10 mN/m and a temperature of 20 °C showing the dark, chiral liquid condensed domains in a continuous matrix of bright liquid expanded phase. (B) DPPC at the surface pressure of 25 mN/m and a temperature of 30 °C; the liquid condensed domains are much smaller. (C) DPPC at the surface pressure of 40 mN/m and the temperature of 37 °C. Only the liquid expanded phase is visible at these conditions.

Figure 8. (A) Terminal velocity of the magnetic needle on monolayers of DPPC as a function of surface pressure and temperature, normalized to the speed of the needle on a clean subphase–air interface, v/v. The constant normalized terminal needle velocity at 37 °C shows that there is no change in the subphase drag as a function of the surface pressure, which justifies the assumptions inherent in eqs 4–8. (B) Surface shear viscosity of a monolayer of DPPC as a function of surface pressure and temperature. The surface shear viscosity was calculated from eq 11 using the calibration in Figure 6. For the 20, 25, and 30 °C data, the slopes of the normalized speed and the surface viscosity plots change abruptly at surface pressures that correspond to the LE–LC transition pressure at that temperature. At 37 °C, the surface viscosity cannot be resolved with this instrument; essentially all of the drag on the needle is from the subphase rather than from the DPPC monolayer.

There could also be a shear rate dependence of the viscosity for DPPC; the shear rates in the canal viscometer were likely different than those used here. The shear rates in our experiments can be roughly approximated by the needle speed (0–1.5 cm/s) divided by the half-width of the channel (0.6 cm), or shear rates of 0–2.5 s⁻¹.

As currently configured, the magnetic needle viscometer has a range of 0.001–1.0 P cm, which is useful for many monolayers in the LC phase and for LE–LC coexistence over a range of surface pressures from 0 to about 50 mN/m. Surface viscosities lower than 0.001 P cm cannot be easily resolved due to the subphase drag with the current configuration. From eq 7, the contribution of the drag from the subphase is proportional to the contact area between the needle and the subphase and inversely proportional to the characteristic length scales over which the velocity decays in the subphase. To increase the sensitivity of the viscometer to less viscous monolayers, it would be necessary to switch to a smaller diameter needle (maximize \( P_c/a_c \), the ratio of the needle perimeter in contact with the monolayer to the needle surface area in contact with the subphase). In their viscometer, Brooks et al. use a thin magnetized iron wire of much smaller diameter (about 0.2 mm) which provides greater sensitivity to the monolayer, but the relatively high density (compared to water) of the solid iron wire reduces the range of surface pressures that can be investigated.¹¹ For our purposes, the variation in the magnetization of the iron wire would add complications to the experiment, as the force on the needle would not be constant with time. We use the smallest available commercial permanent magnet that we have found in our needle assembly; the permanent magnet ensures that we have a constant magnetic moment and hence a constant force on the needle. Increasing the length of the Teflon tube in which the magnet is encased would lower the density of the needle and increase the upper range of surface pressures we can investigate. Increasing the channel depth and decreasing the channel width should also improve the sensitivity of the viscometer to the surface viscosity (increasing \( L_c'/L_c'' \), the length scales for subphase and surface dissipation in eq 7). Further optimization of the needle assembly, or use of different needle assemblies for different monolayers, is likely required to increase the range of application of the viscometer to higher surface pressures and lower surface viscosities.

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