A Constant Torque Micro-Viscometer
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ABSTRACT
We present a technique to measure the viscosity of microscopic volumes of liquid using rotating optical tweezers. The technique can be used when only microlitre (or less) sample volumes are available, for example biological or medical samples, or to make local measurements in complicated micro-structures such as cells. The rotation of the optical tweezers is achieved using the polarisation of the trapping light to rotate a trapped birefringent spherical crystal, called vaterite. Transfer of angular momentum from a circularly polarised beam to the particle causes the rotation. The transmitted light can then be analysed to determine the applied torque to the particle and its rotation rate. The applied torque is determined from the change in the circular polarisation of the beam caused by the vaterite and the rotation rate is used to find the viscous drag on the rotating spherical particle. The viscosity of the surrounding liquid can then be determined. Using this technique we measured the viscosity of liquids at room temperature, which agree well with tabulated values. We also study the local heating effects due to absorption of the trapping laser beam. We report heating of 50-70 K/W in the region of liquid surrounding the particle.

Keywords: Microrheology, Optical Tweezers

1. INTRODUCTION
Optical tweezers are a tool developed by Ashkin et al. in 1986 which allows for the manipulation of microscopic particles. A gradient optical trap is generated by a tightly focused laser beam, at the focus of which micron sized transparent particles can be trapped. The trapping force results from the transfer of linear momentum from the light beam to the particle. Since the first demonstration of optical tweezers, many enhancements have been made to allow for quantitative measurements of microscopic systems. Detection systems have been developed that allow piconewton forces to be measured, making optical tweezers ideal for force measurements of biological systems. They have also been used to measure viscoelastic properties of complex fluids on a microscopic scale.

Not only translational manipulation is possible, controlled rotation of particles has also been demonstrated. Angular momentum, spin or orbital, is transferred from the trapping laser to the particle causing rotation due to optical torque transfer. Measurement of this rotation and optical torque, have allowed for quantitative measurements using rotational motion to be made, in particular viscosity measurements.

We present in this paper a micro-viscometer that uses rotation and optical torque measurement to determine viscosity in different types of liquid and is an extension towards a micro-rheometer.

Microrheology is the study of flows within microscopic volumes of fluids. Our micro-viscometer is able to make such studies using a microscopic probe particle and studying its interaction with the surrounding liquid. In order to investigate a specific region within the fluid, manipulation of the particle is required. We use optical tweezers to both manipulate the probe particle, and to study its interaction with the surrounding liquid. Rheology on these size scales has previously been measured by using single and dual particle tracking techniques, as well as dual optical trap correlation measurements. These techniques allow the viscoelastic properties of the surrounding liquid to be measured. However, they are passive methods which do not allow stress induced properties, such as shear thinning in non-Newtonian fluids, to be observed. Our micro-viscometer applies a controlled stress to the surrounding fluid, therefore such effects can be studied. This technique has the advantage over translation techniques that it does not require a trap stiffness calibration, and also the rotational motion requires a much smaller volume than if translational motion is used to study a fluid. This means that the properties of fluids inside membranes and cells can be measured.

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2. THEORY

In this study we concentrated on the viscous properties of a liquid. The viscosity of a Newtonian fluid is given by

\[ \mu = \frac{\alpha}{\dot{\gamma}} \]  

(1)

where \( \alpha \) is the shear stress and \( \dot{\gamma} \) is shear rate. Effectively this is the ratio of stress to strain in a fluid. The strain is the fluid’s response to an applied stress. We measure viscosity by applying a known and controlled stress, which is achieved by rotating a sphere with a controlled torque that is applied optically using the trapping laser. To explain how a torque can be applied, and at the same time measured,\textsuperscript{10} we begin by representing the trapping beam as a sum of two circularly polarised components and defining a ‘degree of circular polarisation’

\[ \sigma = \frac{P_L - P_R}{P_L + P_R} \]  

(2)

where \( P_L \) and \( P_R \) are the powers associated with the left and right circularly polarised components respectively. A change in either of these two components as the beam passes through a birefringent particle results in a change in the total angular momentum flux of the beam and the transfer of angular momentum from the beam to the particle. The resulting reaction torque on the particle is given by\textsuperscript{10}

\[ \tau_R = \frac{\Delta \sigma P}{\omega} \]  

(3)

where \( \Delta \sigma \) is the change in the degree of circular polarisation as the beam passes through the particle, \( P \) is the laser power and \( \omega \) is the optical angular frequency. This reaction torque \( (\tau_R) \) on the sphere due to the polarisation change of the incident light means that a constant stress is applied to the surrounding liquid. The response of the liquid, or the strain, results in a viscous drag torque acting on the sphere given by\textsuperscript{11}

\[ \tau_D = 8\pi \mu a^3 \Omega \]  

(4)

where \( \mu \) is the viscosity of the surrounding liquid, \( a \) is the radius of the sphere and \( \Omega \) is its angular frequency. This expression assumes low Reynolds number flows and that the surrounding fluid is Newtonian, so that the elastic response of the fluid can be ignored. Both of these assumptions are valid for fluids like water and methanol on the size scale relevant to optical tweezers. For conservation of momentum the reaction torque must be equal to the viscous drag torque \( (\tau_R = \tau_D) \) which gives an expression for the fluids viscosity

\[ \mu = \frac{\Delta \sigma P}{8\pi a^3 \Omega \omega} \]  

(5)

in which all the parameters can be experimentally determined.

As the laser causes some heating of the fluid surrounding the sphere the temperature dependence of viscosity needs to be considered. The temperature dependence can be studied by varying the laser power of the trapping beam. This dependence for Newtonian fluids can be described approximately by\textsuperscript{12}

\[ \mu = Ae^{-B/T} \]  

(6)

where \( T \) is the temperature and \( A \) and \( B \) are constants that can be found experimentally for different fluids. If we assume that the temperature increase due to laser heating is linear then the temperature as a function of laser power is given by

\[ T = CP + T_0 \]  

(7)

where \( P \) is the laser power, \( T_0 \) is room temperature and \( C \) is a constant. Using equations 6 and 7 we can determine the viscosity of our sample fluid at room temperature and the local temperature increase near the particle due to laser heating.
The experimental setup consists of a typical optical tweezers setup combined with a detection system that analyses the transmitted laser light, and is shown in figure 1. The trapping laser used in the experiment was a NdYAG laser (Crystal Laser), producing linearly polarised light with a wavelength of 1064nm and a power output of 800mW. The power was varied by rotating the plane of polarisation in front of a polarising beam splitter cube using a half wave plate. The beam was expanded using a telescope and then directed through a quarter wave plate, so the light was circularly polarised, to an Olympus oil immersion 100 times magnification objective (P100) with a numerical aperture of 1.3. The beam was focused to a sample, held on a piezo driven XYZ translation stage, then collected by an oil immersion condenser with a numerical aperture of 1.4 to ensure that all the transmitted laser light was collected. The collected light was directed to a mirror that allowed a tiny fraction of a linearly polarised component through to a photodetector. The reflected beam was directed to a circularly polarised component detection system, which consisted of a quarter waveplate followed by a polarising beam splitter and two photodetectors. One of these detectors then measured the left handed circularly polarised component, and the second detector measured the right handed circularly polarised component.

The photodetector that measures the linear polarisation component of laser light transmitted through the microscope is used to determine the angular frequency of the vaterite particle rotating in the optical trap. A typical signal from this detector is shown in figure 2(a), which shows a sinusoidal variation with time. The frequency of this variation is the frequency of rotation of the plane of polarisation and hence the rotation of the optical axis of the vaterite particle. The two fold optical symmetry of the particle means the particle’s
Figure 2. The plots show the signals from the three detectors that analysed the transmitted light. The linearly polarised component (a) varied sinusoidally with twice the frequency of the rotating particle (due to the two fold optical symmetry of the vaterite). The two circularly polarised components (b) show the change in polarisation as the beam passed through the vaterite particle.

The vaterite particle that is rotated in the optical tweezers is a calcium carbonate mineral that can be grown to form spherical crystals. Vaterite is birefringent, similar to calcite, and typically grows to a size of 2-5 µm. The technique we use to grow these crystals has been previously published. The fluids used in our experiments were water, ethanol, methanol and hyaluronic acid (HA). HA is a polysaccharide found in animals and humans, this particular sample is from rooster’s comb. It is an example of a complicated biopolymer that exhibits visco-elastic properties. The concentration of the sample used was 1.5 g/L.

4. RESULTS

The micro-viscometer was tested using Newtonian fluids with well known viscosities and viscosity temperature dependence. These fluids were water, ethanol and methanol. The viscosity was measured for different laser powers so that the viscosity at different shear rates could be determined. The result of this for methanol is plotted in figure 3(a) and shows that the viscosity varies with varying laser power. The measured viscosity is not constant with power as laser induced heating causes the local temperature of the liquid to rise as the power is increased. The data is fitted using equations 6 and 7 to determine the viscosity at room temperature and the temperature rise due to laser heating. This process was repeated for particles of different sizes and figure 3(b) shows this result. From these measurements the mean viscosity was found to be 0.542 cP (centiPoise) at room temperature, with a standard deviation of 0.021 cP. This result agrees well with the accepted viscosity of methanol which is 0.56 cP. The typical temperature rise measured for these particles was about 60 K per Watt of laser power.
Figure 3. Plot (a) show the viscosity’s dependence on laser power for methanol. Plot (b) shows the variation in measured viscosity when particles of different diameters were used. The small variation suggests measurements can be made within this particle size range (approximately 2-5 µm).

Figure 4. The plot shows the viscosity’s dependence on laser power for the non-Newtonian fluid hyaluronic acid (HA).

More complicated fluids could now be studied using the characterised micro-viscometer. Hyaluronic acid has exhibited non-Newtonian effects, such as shear thinning, in macrorheology experiments, so is an example of a more complicated fluid. The plot in figure 4 shows the dependence of HA’s viscosity on the trapping laser power. The form of the fit is the same as that used for methanol and therefore assumes a Newtonian behaviour of the fluid. The viscosity at room temperature of HA was measured to be 9.65 ± 0.44 cP.

5. DISCUSSION

The viscosity measurements using the micro-viscometer in Newtonian fluids agree well with the accepted values at room temperature, and so the method is successful in this regard. However the second result, the laser induced heating, is more interesting. Local temperature increases due to the laser in water surrounding trapped transparent particles has previously been reported within the range of 5-15 K/W. Here we report an increase

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of 50-70 K/W in the local fluid region around the particle. On this basis we must assume that the absorption of the laser power is dominated by absorption in the particle.

The results from the measurements of HA seem to suggest that HA acts as a Newtonian fluid within the range of shear rates accessible by our micro-viscometer. However the viscosity indicated in the plot in figure 4 is a function of laser power and therefore temperature dependent and shear rate dependent. The fit assumes only a temperature dependence and therefore if there is any dependence on the shear rate it would be difficult to extract this information from the plot. However there are two factors that suggest our analysis is valid. The first is that for non-Newtonian fluid, we might expect to observe shear thinning. Shear thinning would mean that at a certain shear rate and above, the viscosity would begin to decrease with increasing shear rate. However this effect is not observed at any point on the relatively monotonic viscosity versus power curve. The second factor is that the data fits the temperature dependent curve very well suggesting that this simple model is valid.

6. CONCLUSIONS AND OUTLOOK

We have successfully demonstrated a constant torque micro-viscometer with which we were able to make room temperature measurements of viscosity for three liquids of known viscosity and one liquid (HA) with an unknown viscosity. The heating effect due to the trapping laser beam was accounted for by a simple model. This could be improved by taking better account of temperature gradients surrounding the particle. The amount of heating observed suggests that heating must occur due to absorption of laser light by the vaterite particle. We intend to make experiments using liquids that do not absorb at 1064nm, such as heavy water ($D_2O$). Another possibility is to investigate the use of other birefringent particles.

A fluid (HA) which is known to exhibit non-Newtonian effects was also studied. The viscosity as a function of shear rate curve did not show any evidence of shear thinning. We believe however that the shear stress applied by the micro-viscometer is not great enough to access the shear thinning region reported in HA. In order to study these kind of effects different polymer solutions could be used that are known to exhibit shear thinning at lower shear rates.

REFERENCES


