The cone-and-plate geometry

In the cone-and-plate geometry, the test sample is contained between an upper rotating cone and a stationary flat plate (see Figure 2.5, upper). In the example shown, the cone is 40 mm in diameter, with a cone angle of 1° 59' relative to the plate, and a truncation of 51 µm.

Figure 2.5  Cone-and-plate (upper) and parallel plate (lower) geometries
The small cone angle (<4°) ensures that the shear rate is constant throughout the shearing gap, this being of particular advantage when investigating time-dependent systems because all elements of the sample experience the same shear history, but the small angle can lead to serious errors arising from eccentricities and misalignment.

The small gap size dictates the practical constraints for the geometry: a gap-to-maximum particle (or aggregate) size ratio of >100 is desirable to ensure the adequate measurement of bulk material properties. This geometry is, therefore, limited to systems containing small particles or aggregates, and the strain sensitivity is fixed. Normal stress differences may be determined from pressure and thrust measurements on the plate.

The form factors for the cone-and-plate geometry are as follows:

Shear stress:
\[
\tau = \frac{3T}{2\pi R^3} 
\]

Shear rate:
\[
\dot{\gamma} = \frac{\Omega \tan \alpha}{\tan \alpha} 
\]

where \( R \) is the radius of the cone (m), \( T \), the torque (Nm), \( \Omega \), the angular velocity (rad/s) and \( \alpha \), the cone angle (rad).

The influence of geometry misalignment and other factors, such as flow instabilities arising from fluid elasticity, have been extensively studied in the case of this geometry [Macosko, 1994]. Unlike the concentric cylinder geometry, where fluid inertia causes a depression around the inner cylinder rather than the well-known ‘rod-climbing’ effect due to visco-elastic normal stresses, in the cone-and-plate geometry the effect of inertia is to draw the plates together, rather than push them apart [Walters, 1975].

Many experimentalists employ a ‘sea’ of liquid around the cone (often referred to as a ‘drowned edge’), partly in an attempt to satisfy the requirement that the velocity field be maintained to the edge of the geometry.

2.3.4 The parallel plate geometry

In this measuring geometry the sample is contained between an upper rotating or oscillating flat stainless steel plate and a lower stationary plate (see Figure 2.5, lower). The upper plate in the example shown is 40 mm in diameter. In contrast to the cone-and-plate geometry, the shear strain is proportional to the gap height, \( h \), and may be varied to adjust the sensitivity of shear rate, a feature which readily facilitates testing for wall (slip) effects [Yoshimura and Prud’homme, 1988].

The large gap sizes available can be used to overcome the limitations encountered using the cone-and-plate geometry, such as its sensitivity to
eccentricities and misalignment. However, it should be borne in mind that, as in the case of the wide-gap Couette devices, shear rate is not constant. Usually the strain reported is that measured at the outer rim, which provides a maximum value of the spatially varying strain within the gap.

Loading and unloading of samples can often prove easier than in the cone-and-plate or concentric cylinder geometries, particularly in the case of highly viscous liquids or ‘soft solids’ such as foods, gels etc. The parallel plate geometry is particularly useful for obtaining apparent viscosity and normal stress data at high shear rates, the latter being increased either by increasing $\Omega$ or by decreasing the shearing gapsize. An additional benefit of the latter approach is that errors due to secondary flows, edge effects and shear heating may all be reduced.

Form factors for the parallel plate geometry, in terms of the apparent or Newtonian shear stress and the shear rate at $r = R$ are given below:

Shear stress:

$$\tau = \frac{2T}{\pi R^3}$$

Shear rate:

$$\dot{\gamma} = \frac{\Omega R}{h}$$

where $h$ is the plate separation (m), $\Omega$, is the angular velocity (rad/s), and $R$, is the plate radius (m). A full derivation of the working equations may be found elsewhere [e.g. Macosko, 1994].

2.3.5 Moisture loss prevention – the vapour hood

When dealing with high concentration samples of low volume, even low moisture loss can have a critical effect on measured rheological properties [Barnes et al., 1989]. During prolonged experiments, moisture loss may be minimised by employing a vapour hood incorporating a solvent trap, as shown in Figure 2.6.

As noted above, edge effects can be encountered with each of the geometries considered here. They become of particular importance when dealing with samples which form a surface ‘skin’ in contact with the atmosphere, due mainly to evaporation. Conditions at the outer edge of the parallel plate and cone-and-plate geometries strongly influence the measured torque value. Stresses in this region act on a larger area and are operating at the greatest radius. To ensure homogeneous bulk sample conditions, the evaporation process at the sample surface may be minimised by employing a vapour hood, as shown in Figure 2.6 for the parallel plate system.
2.4 The controlled stress rheometer

Since the mid 1980s and the advent of reliable ‘second generation’ controlled-stress rheometers, the controlled-stress technique has become widely established. The facility which most of this type of instrument offers, i.e. of performing three different types of test (steady shear, oscillation and creep), makes them particularly cost effective.

The instrument referred to here for illustration is a TA Instruments CSL 100 controlled-stress rheometer (TA Instruments, UK). The rheometer (typically operated under the control of a microcomputer) and ancillary equipment required for its operation, consist of the following main components (see Figure 2.7).

An electronically-controlled induction motor incorporates an air bearing, which supports and centres a rotating hollow spindle. The spindle incorporates a threaded draw rod, onto which the components of the required measuring geometry is secured and the air bearing prevents any contact between fixed and moving parts. A digital encoder consisting of a light source and a photocell is arranged either side of a transparent disc attached to the spindle. Fine lines (similar to diffraction grating lines) are photographically etched around the disc edge and, through the use of a stationary diffraction grating between the light source and the disc, diffraction patterns are set up as the disc moves under an applied torque. These are directly related to the angular displacement of the measuring system.

The non-rotating lower platen of the measuring assembly is fixed to a height-adjustable pneumatic ram which may be raised to provide the desired gap setting, with micrometer-fine adjustment. A temperature control unit is

![Figure 2.6 Vapour hood employed with a parallel plate geometry](image-url)
incorporated within the lower plate. This is usually of the peltier type, using a thermoelectric effect enabling it to function as a heat pump with no moving parts. Control of the magnitude and direction of the electrical current allows the desired temperature adjustment within the lower platen (control to 0.1°C), and thus within the sample, for cone-and-plate and parallel plate geometries. For the concentric cylinder geometry a temperature-controlled recirculating water bath is generally used.

Due in part to its ability to produce extremely low shear rates, the controlled stress technique has been found to be highly suited to the determination of apparent yield stress, and in this respect the controlled-stress instrument is widely claimed to be more successful than its controlled-shear rate-counterparts. This is usually attributed to the fact that, for suitably low stresses, the structure of the material may be preserved under the conditions of test. Indeed, the introduction of the ‘second generation’ of controlled-stress instruments can be said to have provoked considerable interest in, and debate surrounding, the field of yield stress determination, with some early advocates of the controlled-stress technique advancing the controversial notion of the ‘yield stress myth’ [Barnes and Walters, 1985].

Apart from the range of instruments described in the preceding sections, several of the inexpensive viscometers used for quality control in industry give rise to complicated flow and stress fields (which may be neither known nor
uniform), but they have the great advantage that their operation is simple. In the case of Newtonian fluids, the use of such methods does not pose any problem, since the instruments can be calibrated against a standard Newtonian liquid of known viscosity. However, for non-Newtonian fluids, the analysis and interpretation of results obtained by using such devices is not simple and straightforward. Such devices can be broadly classified into two types. The first have what might loosely be called “flow constrictions”, as exemplified by the Ford cup arrangement, in which the time taken for a fixed volume of liquid to drain through the constriction is measured. Such a device can cope with different ranges of viscosities by changing the size of the constriction. This robust and convenient instrument is used widely in the petroleum and oil industries. The second class of instruments involves the flow around an obstruction as in the falling ball and rolling ball methods [van Wazer et al., 1963] where the time taken for the sphere to settle or roll through a known distance is measured. Although such “shop-floor” viscometers can perhaps be used for qualitative comparative purposes for purely inelastic fluids, great care needs to be exercised when attempting to characterise visco-elastic and time-dependent non-Newtonian materials even qualitatively [Barnes et al., 1989; Chhabra, 1993].