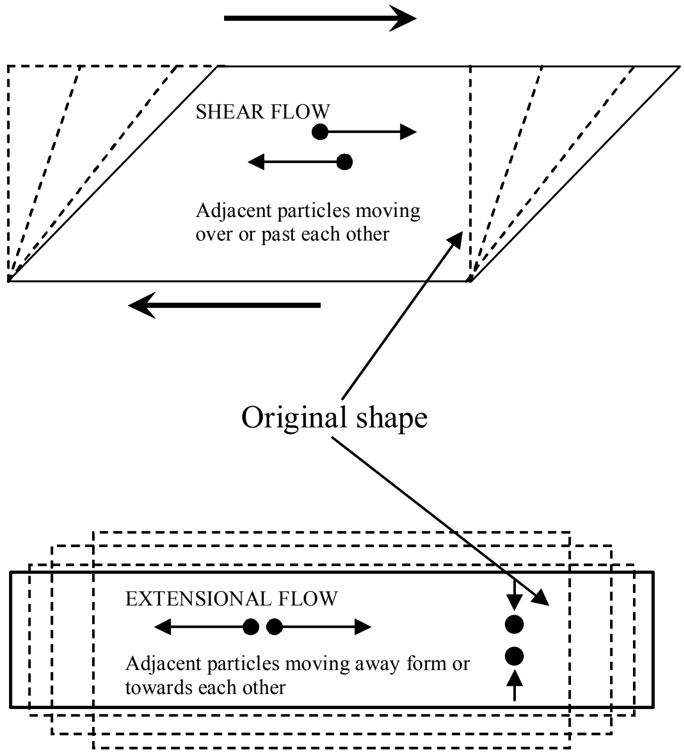

Figure 3.5 Particle motion in shear and extensional flows.

Two different rheological techniques have been used in this work, rotational rheometry, allowing the study of the shear flow, and high pressure capillary rheometry, allowing the study of both shear and extensional flow.

3.2.3.1 Rotational rheology

Viscosity is the internal friction of a fluid or its tendency to resist to flow. Liquids are made to flow by imparting a velocity by applying a force. For a given velocity the resulting force increases when the viscosity is increased, whereas for a given force, the velocity is reduced when the viscosity is increased. In Figure 3.6 the shear flow is visualized as the movement of hypothetical layers of fluid sliding over each other. In the simplistic case the velocity of each layer increases linearly with respect to its neighbour below, so that the layers twice the distance from any stationary edge move at double the speed. The gradient of the velocity in the direction at right angles to the flow is called shear rate ($\dot{\gamma}$). In this simple example, the shear rate is the ratio between the velocity u and the distance h of the layer from the stationary edge. The force per unit area creating or produced by the flow is called the shear stress (σ = F/A). The apparent viscosity (η_a) is the ratio between the shear stress and the shear rate

$$\eta_a = \frac{\text{Shear Stress}}{\text{Shear rate}} = \frac{\sigma}{\dot{\gamma}}. \qquad \text{Eq 3.4}$$

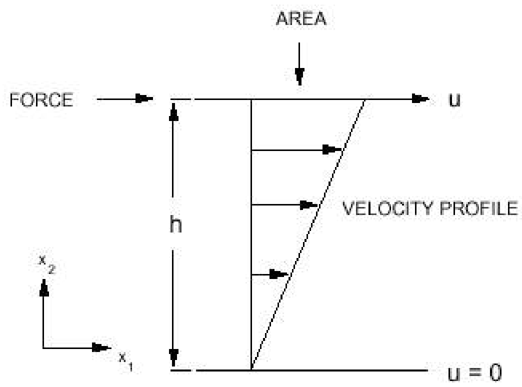

Figure 3.6 Shear flow

3.2.3.1.1 Principle of operation of rotational rheometers and viscometers.

The principal components of a controlled stress Rheometer are shown in Figure 3.7.

The rheometer has a constant torque motor which works through a drag cup system. An angular position sensor detects the movement of the measuring system attached to the shaft.

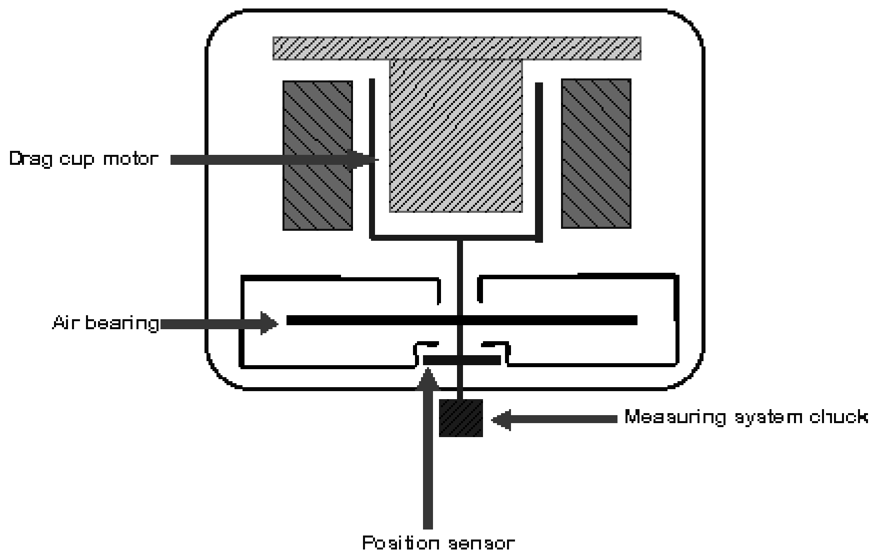

Figure 3.7 Components of a controlled stress rheometer

Modern rheometers have software that automatically converts the applied value of torque to a shear stress when displaying data. The reading from the position sensor is converted to a strain. The conversion factors used depend on the type of measuring system.

The principal components of a controlled rate rheometer are shown in Figure 3.8.

The rheometer is a constant speed motor with a torque detection system. The torsion bar is suspended on an air bearing to give a virtually frictionless bearing.

When the drive system turns, the sample resistance (viscosity) tries to twist the torsion bar. By measuring the resultant twist and knowing the stiffness of the bar, the torque is obtained.

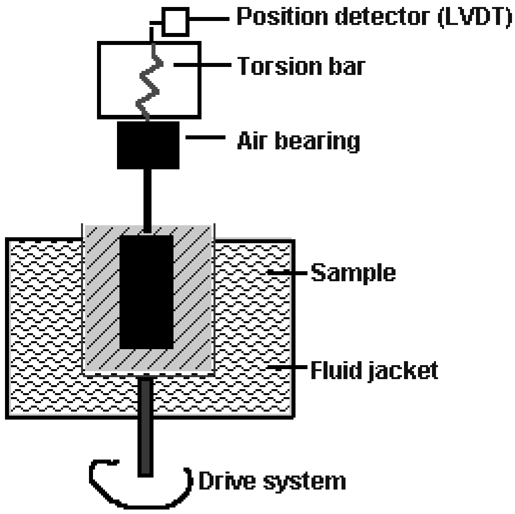

Figure 3.8 Components of a controlled rate rheometer

The measuring systems used in this work were:

(1) Cone and Plate
(2) Parallel Plates
(3) Cup and bob

The choice of the appropriate geometry depended on the kind of test need to perform and on the physical characteristic of the material analyzed.

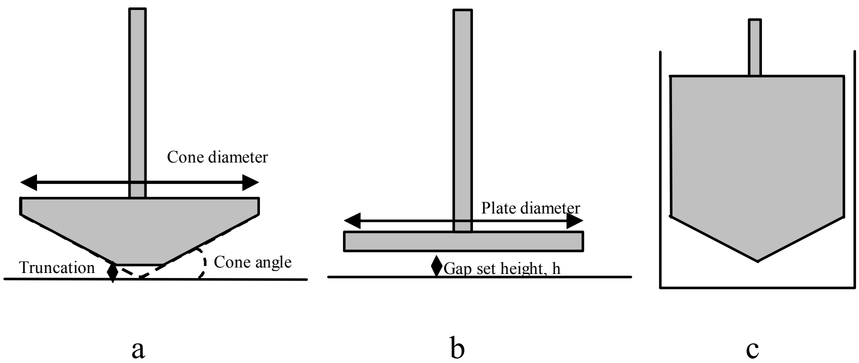

Figure 3.9 Cone plate (a), parallel plate (b) and cylindrical concentric geometries (c)

Figure 3.9 shows a schematic representation of the cone plate (a), parallel plate (b) geometries and cylindrical concentric geometry (c).

The torque and angular velocity is multiplied by the "form factors" C_1, and C_2 to give the shear stress, σ, and the shear rate, $\dot{\gamma}$, respectively.

Shear Stress $\sigma = C_1 \times M$ Eq. 3.5

Shear Rate $\dot{\gamma} = C_2 \times \omega$ Eq. 3.6

Viscosity $\eta = \sigma / \dot{\gamma}$ Eq. 3.7

Where M is the torque and ω is the angular velocity

For some measuring systems such as parallel plates, the gap between the measuring systems can be set by the user. In this case the equation used is :

$$\dot{\gamma} = \frac{C_2 \times \omega}{L} \quad \text{Eq. 3.8}$$

where L is the gap.

Form factors are associated with the measuring systems and the equation are shown in the following sections.

Cone plate $C_1 = \dfrac{1}{\frac{2}{3}\pi r^3}$ and $C_2 = \dfrac{1}{\theta}$ Eq. 3.9

Where r = radius of cone θ= cone angle in radians

Parallel plates $C_1 = \dfrac{1}{\frac{2}{3}\pi r^3}$ and $C_2 = \dfrac{3r}{4}$ Eq. 3.10

Where r = radius of plate

Because for a parallel plate the shear stress varies across the radius, the above formula refers to the 3/4 radius position if the test sample is Newtonian.

Coaxial cylinders $C_1 = \dfrac{1}{2\pi r_a^2 H}$ and $C_2 = \dfrac{2r_i^2 r_0^2}{r_a^2 (r_0^2 - r_i^2)}$ Eq. 3.11

Where $r_a = (r_i + r_0) / 2$
r_i = inner radius
r_0 = outer radius
H = height of cylinder

3.2.3.1.2 Flow characterization

3.2.3.1.2.1 Flow curves

Rheometers of this type can monitor the apparent viscosity when the shear stress or the shear rate is varied. The measured viscosity of a fluid can often be seen to behave in one of four ways when sheared, namely:

1 Viscosity remains constant no matter what the shear rate (Newtonian behaviour)

2 Viscosity decreases as shear rate is increased (shear thinning behaviour)

3 Viscosity increases as shear rate is increased (shear thickening behaviour)

4 Viscosity appears to be infinite until a certain shear stress is achieved (plastic behaviour)