CHAPTER I

INTRODUCTION

The flow of solid-in-liquid suspensions is frequently encountered in chemical and other fields of engineering and therefore, the knowledge of their rheological behaviour becomes indispensable for their flow characterisation specially in mixing, pumping, transportation and heat transfer problems.

The nature of suspensions widely vary for they may be stable, upward settling, slow or rapidly settling types. These suspensions are found to behave like non-Newtonian fluids under the viscous flow conditions but most of them behave like Newtonian fluids under turbulent conditions. Therefore, under turbulent conditions single point method of viscosity determination can be applied satisfactorily. Nevertheless the rheological behaviour of homogeneous suspensions is a function of intrinsic physical properties of the solids such as concentration, size, shape, size distribution and surface characteristics etc.

The first mathematical formulation with regard to the viscosity of suspensions was proposed by Einstein (11), who from the hydrodynamic considerations of the solid particles suspended in liquid, derived the following correlation,

$$\mu_{sl} = (1 + 2.5x_v)\mu_l \qquad .. \qquad (1.1)$$

where, μ_{sl} , μ_l and x_v are viscosity of suspension, viscosity of suspending medium and volume fraction of the solids respectively. This equation is valid for very dilute suspensions (x_v 0.05) of rigid, monodispersed, spherical and free flowing solids suspended in Newtonian fluids forming stable suspensions.

For the prediction of apparent viscosity of suspensions at moderate and higher concentrations the Einstein equation has been modified by number of workers. Bingham and Durham (2) studied the various solid suspensions with low and moderate solids concentrations (x_v upto 0.09) and showed that the fluidity of the suspension decreased rapidly and linearly as the solids concentration was increased. Drucker and Kassel (9) and White(53) observed that the fluidities of the homogeneous suspensions are normally additive.

Ford (15) showed that Equation 1.1 in the fluidity form and its expansion as a binomial expression gave a better approximation for estimating the viscosity of the suspensions at low and moderate concentrations. He proposed the following equation,

$$\phi_{sl} = \phi_{l}(1 - 2.5\, x_v) \qquad .. \quad (1.2)$$

where ϕ_{sl} and ϕ_{l} are the fluidities of suspensions and suspending medium respectively.

Happle (19) gave a correlation similar to the Einstein equation for the prediction of the viscosity of concentrated suspensions of rigid monodispersed spherical particles, which is as follows,

$$\mu_{sl} = (1 + 5.5\,\Psi' x_v)\mu_l \qquad .. \qquad (1.3)$$

where, Ψ' is the interaction factor.

By taking into ~~the~~ account the hydrodynamic interaction between the particles, Vand(46) and others (3,7,12,17,18) suggested the expressions in the form of power series to predict the viscosity of suspensions upto 50 per cent solids concentration. The generalised form of these expressions is,

$$\mu_{sl} = \mu_l \left[1 + A_1 x_v + A_2 x_v^2 + A_3 x_v^3 + \ldots\ldots \right] .. \qquad (1.4)$$

where, A_1, A_2 and A_3 are constants which vary in the range - $2.5 < A_1 < 5.5$, $2.5 < A_2 < 14.1$ and $2.5 < A_3 < 36.3$ respectively. These equations however are not very accurate beyond 30 per cent solids concentration. The alternative expression by Thomas (44) which could be used satisfactorily for the solids below 20 microns size, is as follows,

$$\frac{\mu_{sl}}{\mu_l} = 1 + 2.5\,x_v + 10.05\,x_v^2 + 0.062\,\exp\left[\frac{1.875\,x_v}{1-1.595x_v}\right] .. \qquad (1.5)$$

Robinson(36) showed that, for suspensions of rigid spheres, the specific viscosity of suspensions is directly proportional to solids volume fraction and inversely proportional to the liquid volume fraction. He proposed the following relation,

$$\frac{\mu_{sl} - \mu_l}{\mu_l} = \frac{K' x_v}{(1 - Y x_v)} \qquad .. \qquad (1.6)$$

where, K' is Einsteins constant, Y is $(\frac{1}{1-\varepsilon})$ and ε is the porosity of the bed in the randomly packed spheres. His data showed that the packed sediment volume is approximately equal to the effective volume of the particles.

Ting and Luebbers (45) studied the viscosity behaviour of suspensions of spherical and other isodimensional particles upto 50 per cent solids concentration by volume and derived the following expression,

$$\frac{x_v}{\mu_{sp}} = x_{v,\infty} - x_v \qquad .. \qquad (1.7)$$

where, μ_{sp} is the specific viscosity $(\frac{\mu_{sl} - \mu_l}{\mu_l})$ and $x_{v,\infty}$ is the volume fraction of solids at which the viscosity of suspension tends to be infinity.

Mooney (28) proposed a theoretical equation to predict the viscosity of the spherical particles,

$$\frac{\mu_{sl}}{\mu_l} = \exp \left[2.5\, x_v / (1 - \Psi\, x_v) \right] \qquad .. \qquad (1.8)$$

where, Ψ is the self crowding factor.

Frankel and Acrivos (16) gave a theoretical expression for the viscosity of suspensions of spherical particles upto maximum attainable solids concentration taking into account the hydrodynamic interactions between the particles. The expression is as follows,

$$\frac{\mu_{s1}}{\mu_1} = \frac{9}{8}\left(\frac{x_v/x_{v,m}}{1 - x_v/x_{v,m}}\right)^{1/3} \qquad .. \qquad (1.9)$$

where, $x_{v,m}$ is the maximum attainable concentration.

All the above studies have been carried out with monodispersed, rigid spherical particles with particular reference to the effect of solids concentration on the viscosity. Only limited work has been reported on the effects of other parameters such as particle size, shape, size distribution, surface characteristics of the solids and rate of settling on the rheological behaviour of the suspensions.

In the literature there are contradictory reports about the effect of particle size on the viscosity of suspensions. Weltmann and Green (52), Moreland (29) and Others (31,34,43,49,53) have reported the increase in the viscosity of suspension with decrease in the particle size for the same solids concentration. Whereas, Kustov and Khotuntzev (24) and Schack et al (40) have reported the opposite trend.

The effect of particle shape or irregularity on the rheological behaviour of suspensions have been reported by a number of workers (4,8,17,22,29,37,41,45,51). In general it has been found that the viscosity of suspensions of irregular particles is higher than that of smooth and spherical particle suspensions.

The effect of particle size distribution on the rheological properties of suspensions have been studied by Ward and Whitmore(50), Roscoc(39) and Others (26,27,28,29,39,43). It has been reported that the viscosity of suspensions could be considerably decreased by blending carefully the different particle sizes.

It has been observed (5,30,49) that when the solids are suspended in the liquid, each particle gets surrounded by a stagnant liquid layer known ~~on~~ as lyosphere, and the thickness of lyosphere depends on the size and surface characteristics of the solids.

Limited information on the rheological behaviour of unstable suspensions is available in literature (8,33,35,36). Oliver and Ward (31) studied a number of upward and downward settling suspsnsions and found that the Einstein's constant was very sensitive to the change in the stability of suspensions.

Purohit and Roy (35,36) studied a large number of rapidly settling aqueous suspensions. They showed that solids can be classified into two main groups depending on the variation of viscosity with particle size. Further, they proposed a generalised correlation to predict the viscosity of suspensions from the knowledge of the average particle size, solids concentration and viscosity of suspending medium,

$$\left(\frac{\mu_{sl}}{\mu_{sl} - \mu_{l}} \right) = K_1 + K_2 \frac{d_{avg}^{a}}{x_v} \quad .. \quad (1.14)$$

where K_1, K_2 and are constants and are characteristics of a particular system.

It is seen from the above literature survey that the rheological behaviour of suspensions of solid-in-liquid is considerably influenced by the various intrinsic properties of solids. Though the nature of variation of viscosity has been reported,very little information is available about the exact relationship between the change in apparent viscosity with different properties of solids.

The present studies mainly deal with a careful investigation into the effects of solids concentration, size, irregularity and lyosphere thickness on the viscosity of suspensions. The relation between the lyosphere thickness with particle size and surface characteristics also has been investigated. For this purpose aqueous suspensions of five different solids, namely quartz, agate, marble and limestone as irregular particles and glass beads as smooth spherical particles which showed the same trend in the variation of the viscosity with size, were chosen. The studies were carried out in a continuously operating concentric cylindrical type rotational viscometer (Chapter III) in which the bob, fitted with two small paddles at the bottom, driven by a motor, acted as a stirrer and maintained the suspensions in a homogeneous state. The conditions of attaining homogeneity were predetermined in a transparent scale model of the viscometer.

The results obtained enabled the derivation of a generalised correlation for the prediction of apparent viscosity of suspensions from the knowledge of the intrinsic physical properties of solids, lyosphere thickness and viscosity of suspending medium.