C H A P T E R I

I N T R O D U C T I O N

Chapter - I

INTRODUCTION

The knowledge of the rheological properties of solid-in-liquid suspensions is of great importance in many industrial problems. There is an increasing interest in this field in view of the large scale handling of such systems in various chemical processes, transportation of solids as suspensions in pipeline, and a number of proposed uses for examples, prediction of power requirements for agitation, as heat transfer medium, fuel slurry in chemo-nuclear reactors and suspensions of metal powder in jet fuels.

In general, the solid-in-liquid suspensions are non-Newtonian in behaviour and their flow characteristics are influenced by intrinsic and extrinsic properties of solids which include, density, thermal conductivity, specific heat, concentration, size, size distribution, shape, surface characteristics, settling rate etc, and flow regions-viscous, transition and turbulent. However, most of the non-Newtonian suspensions behave like Newtonian in turbulent region and, therefore, a single value of apparent viscosity of the suspension can be obtained and used for design purposes. For these suspensions which continue to show non-Newtonian character in turbulent region, choice of single value is not possible. The properties of these suspensions widely vary. They may be stable, upward settling or rapidly settling type. The influence of factors such as size, shape, concentration, surface characteristics and size distribution of the solid particles on the rheological behaviour of stable and moderately settling suspensions have been stressed by various workers in this field.

Einstein[10] put forward the first fundamental mathematical formulation

$$\mu_{SL} = (1 + 2.5\, x_v)\, \mu_L \qquad ....(i)$$

relating the apparent viscosity of suspension with the volume fraction of solids and the viscosity of suspending medium. This relationship is valid for sufficiently dilute suspensions of free-flowing, monodispersed, rigid spherical particles in Newtonian liquid.

Bingham and Durham[2] studied various suspensions with solids concentration upto 9 percent by volume and showed that the fluidity of suspension decreased rapidly and linearly as the solids concentration increased. Drucker and Kassel[9] and White[36] found that fluidities are normally additive in homogeneous mixtures and fine suspensions.

To describe the flow behaviour of suspensions at higher solids concentration, Einstein's theory has been extended by various workers by considering the hydrodynamic interaction between particles.

Vand[33] derived the following formula for spheres in liquid,

$$\mu_{SL} = (1 + 2.5 x_v + 7.17\, x_v^2 + 16.2\, x_v^3)\, \mu_L \quad ...(ii)$$

He studied glass spheres having an average radius of 0.0065 cm and concentration upto 50 percent by volume. This equation is valid in the relative fluidity range of 1.00 to 0.005.

Happle[14] derived the equation (iii) without any experimental constants to predict the viscosities of concentrated suspensions of uniformly sized spherical particles.

$$\mu_{SL} = (1 + 5.5\, x_v \psi)\, \mu_L \qquad \text{....(iii)}$$

where ψ is the interaction factor.

Ford[12] showed that Einstein equation in its fluidity form and its exact reciprocal that is,

$$\frac{\mu_{SL}}{\mu_L} = (1 + 2.5\, x_v + 6.25\, x_v^2 + \cdots) \qquad \text{...(iv)}$$

may describe accurately the viscosity of suspensions of rigid spheres in Newtonian liquids at low and moderate concentration. Moreland[20] has studied irregular particles of coal in mineral oil and found that for volume concentration of solids of less than 25 percent, his experimental data could be correlated by equation

$$\frac{\mu_L}{\mu_{SL}} = 1 - K x_v \qquad \text{...(v)}$$

where the K is a constant, the value of which depends on the system.

Thomas[31] has proposed the following expression for suspensions of high solids concentration,

$$\frac{\mu_{SL}}{\mu_L} = 1 + 2.5\, x_v + 10.05\, x_v^2 + 0.062 \;\exp \frac{1-0.875\, x_v}{1-1.595\, x_v} \qquad \text{...(vi)}$$

Robinson[26] found that the specific viscosity of the suspension is directly proportional to the volume fraction of the spheres and inversely proportional to the volume fraction of the free liquid in suspension and he developed the equation

$$\frac{\mu_{sl} - \mu_l}{\mu_l} = \frac{K x_v}{1 - y x_v} \qquad \text{.... (vii)}$$

where, K is the Einstein constant, y is $\frac{1}{1-\epsilon}$, and ϵ is the porosity in a bed of random packed spheres. His data show that packed sediment volume is approximately equal to the effective volume of the particles.

Crowley and Kitzes[5] have studied the aqueous thoria slurries and used Robinson equation to correlate their viscosity data. They postulated that the effective volume of the solids was greater than the true volume by virtue of an envelope of fluid, bound to each particle, called " lyosphere " and correlated the thickness of the " lyosphere " with shearstress by the equation

$$\frac{t}{a} = C\,\tau^{-0.02} \qquad \text{....(viii)}$$

where t/a is the ratio of thickness of bound water on the surface of a particle to particle radius and C is a constant dependent on the properties of the particular system.

Murdock and Kearsey[21] have carried out extensive studies on aqueous theria slurries and found that Crowley - Kitzes equation provides the useful correlation of the rheological data for all concentrations of a single slurry.

A number of workers[6,11,16,24,33,35] have investigated the influence of particle size, shape and concentration on the viscosity of stable suspensions. Of these the work of Ting and Luebbers[32] is of particular significance. They have studied systems in which the solids were spherical, cube or rounded particles, and formed stable suspensions in various liquid media. The experimental data obtained were correlated by the equation

$$\frac{x_v}{\mu_{sp}} = x_{v\infty} - x_v \qquad \ldots(ix)$$

where μ_{sp} is the specific viscosity, X_v the volume fraction of solids and $X_{v\infty}$ the volume fraction of solids at which the viscosity of suspension tends to infinity.

Oliver and Ward[23] have studied the influence of departure from stability of suspensions of spherical particles upon their relative viscosities. They found that the relationship between the relative viscosity of settling suspensions and the volume concentration of the solids can be represented by equation

$$\left(1 - \frac{1}{\eta_r}\right) = K x_v + K_1 \qquad \ldots. \quad (x)$$

provided $0.10 < x_v < 0.30$ and for low concentration below 10 percent by

$$\eta_r = (1 + K_2 x_v) \qquad \ldots(xi)$$

where K and K_1 are the slope and intercept of the linear relationship represented by equation (x) and K_2 is equivalent to the Einstein constant. The values of K, K_1 and K_2 have been found to be quite sensitive to the change in stability of the suspensions.

Work[20,27,32,33,38] on the effect of particle size distribution indicate that by careful selection of particle size distribution the viscosity of a suspension can be rendered much lower than those for single sized particles.

In the present investigation, the influence of intrinsic properties of solids such as, concentration, size and shape on the rheological behaviour of a large number of solid-in-liquid suspensions of coal, electrode-graphite, petroleum-coke, selenite, quartz, agate, haematite, in water have been studied. The solids used were irregular in shape, inert to the suspending medium and in the size range of 10 to 314 microns. Most of these suspensions were rapidly settling in nature, and therefore, quick phase separation took place in the absence of adequate agitation. Because of this reason, great difficulty was experienced in determining the apparent viscosity of rapidly settling suspension in conventional capillary or pipeline or rotational viscometer. It was, therefore, found necessary to design and construct a continuously operating concentric cylindrical viscometer in which the inner cylinder fitted with two small paddles at the bottom, driven by a motor, acted as a stirrer.[1,25] The value of viscosity was determined from the measurement of torque developed on the outer cylinder, by a simple mechanical arrangement.

In order to determine the conditions for attaining homogeneity, the settling characteristics were studied in a model viscometer with transparent outer cup. The most striking phenomena observed was the appearance of regularly spaced rings of suspended particles in the liquid medium within a certain speed range of rotation. This phenomena was probably due to instability of heterogeneous fluid between concentric rotating cylinders.

Correlations have been developed to predict the apparent viscosity of suspensions (μ_{SL}) in terms of average diameter of particles (Davg), its volume fraction (X_v) and suspending medium viscosity (μ_L) for all the systems. The general form of equation is

$$\frac{\mu_{SL}}{\mu_{SL} - \mu_L} = k_1 + k_2 \left(\frac{Davg}{x_v} \right)^{a} \qquad \ldots.(xii)$$

where the constants k_1, k_2 and a are the characteristics of a particular systems.