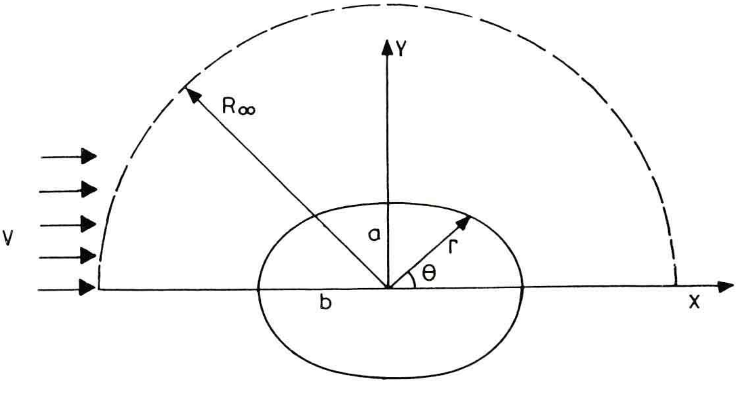
HANDBOOK OF APPLIED POLYMER PROCESSING TECHNOLOGY



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HANDBOOK OF APPLIED POLYMER PROCESSING TECHNOLOGY

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Preface

Polymer processability and processing procedures have evolved into one of the most extensively investigated areas of polymer science over the past decade. The reason for this intense interest is that polymer suppliers have had to learn the difficult and costly lesson that product design in terms of performance in the marketplace often depends on the processing characteristics of the raw material in parts manufacturing operations. Not only must product design take into account end-use performance properties such as adhesion, weather and ozone resistance, chemical resistance, durability, flexural modulus, sealing performance, vibration damping, and a multitude of other end-user requirements, but it must also consider the efficiency of polymer processing operations. Furthermore, many end-use performance properties are a strong function of the processing and rheological characteristics of the elastomer or plastic. A practical example is the manufacture of automotive trunk seals from EPDM. Aesthetics qualities (e.g., surface smoothness, glossiness) that are performance criteria for the consumer depend on such properties as melt fracture and swell. In this example, the extrusion performance of the elastomer plays a critical role in end-performance criteria, as well as extrusion conditions (temperature, pressure, rate), compounding formulation, vulcanization conditions, and the compositional and molecular structure of the elastomer. One cannot simply design a polymeric product with certain end-user performance criteria as targets without addressing the processing steps and characteristics of the polymer along with its active and filler compounding ingredients.

This handbook has been prepared as an industry reference on applied and advanced techniques in polymer processing. It provides some fundamental discussion of rheological properties and concepts but is largely written by experts attempting to develop more rigorous guidance in processability. The handbook contains twenty-seven chapters on advanced subjects of industry concern, and in many discussions the relationships between polymer structural and molecular characteristics are explored in relation to processing properties. The work represents the efforts of a large group of international practitioners. Contributors are to be considered responsible for the statements in their respective chapters. The editors wish to extend deep gratitude to these contributors for their time and effort in the preparation of their treatise and to Marcel Dekker, Inc., for the fine production of this volume.

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1

Hydrodynamics of Nonspherical Particles in Non-Newtonian Fluids

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I. INTRODUCTION

The relative motion between solid particles and a viscous liquid occurs in a variety of operations carried out in chemical, polymer, food, and allied industries. For instance, it is often necessary to estimate the force needed to move a solid object through a liquid, or conversely, the force that a moving liquid exerts on a solid as the fluid flows past it. Many processes for the separation of particles of various sizes, shapes, and densities depend on their behavior when subjected to the action of a moving fluid. Notwithstanding the importance of the detailed kinematics of flow, it is readily recognized that the variable of central interest in all such applications is the free-falling velocity as a function of the properties of the liquid medium (density, viscosity), of the particles (size, shape, and density), and of the operating conditions (size of the apparatus compared to that of the particle, whether the liquid is undergoing any motion, etc.). For the simplest case of the settling of the particle under the influence of the earth's gravitational field in a vast expanse of quiescent viscous medium, the functional relationship between the settling velocity and the pertinent variables is conveniently expressed in terms of the usual dimensionless groups such as Reynolds number and drag coefficient for spherical particles, whereas additional shape factors are needed to quantify the settling behavior of nonspherical particles. Further complications arise depending on whether the shape of the particle is regular or irregular.

Ever since the pioneering work of Stokes in 1851, considerable research effort has been expended in studying the hydrodynamic aspects of sphere motion in Newtonian fluids; consequently, a voluminous body of information has accrued over the last 150 years or so, dealing with different aspects of sphere motion in incompressible Newtonian fluids. Excellent treatises summarizing the rich literature on this subject are available [e.g., see Happel and Brenner (1965), Clift et al. (1978), O'Neill (1981), and Kim and Karrila (1991)].

A spherical particle is unique in that it presents the same projected area to the oncoming fluid irrespective of its orientation. For nonspherical particles, on the other hand, the orientation must be known before their terminal velocity or the drag force can be calculated. Conversely, nonspherical particles tend to attain a preferred or most stable orientation, irrespective of their initial state, in the free-settling process. Vast literature, although not as extensive as that for spherical particles, is also available on the hydrodynamic behavior of nonspherical—regular as well as irregular type—particles in incompressible Newtonian fluids and these studies have been summarized in the aforementioned references, whereas the corresponding aerodynamic literature has been comprehensively reviewed by Hoerner (1965).

Unfortunately, not all liquids of industrial significance exhibit simple Newtonian flow behavior. Indeed, most multiphase mixtures (including foams, emulsions, particulate suspensions), high-molecular-weight substances and their solutions (such as polymers, soaps, gum, proteins), biological fluids (blood, synovial fluid, saliva, etc.), foodstuffs, and so on display complex rheological behavior ranging from simple shear thinning to time-dependent viscoelastic characteristics. Typical instances involving the motion of particles in non-Newtonian fluids include the suspension of heavy abrasive particles in liquid detergents and of heavy proppants in fracturing fluids, pipeline transportation of coarse particles in non-Newtonian carrier fluids, and so forth. Further processes which are strongly influenced by the relative motion between a particle (or particles) and a fluid are encountered in slurry reactors and three-phase fluidized beds, rheometry of particulate suspensions, pastes, and fibre-reinforced plastics. Thus, there is no dearth of industrially important processes involving strong interactions between particles and non-Newtonian media (Chhabra, 1993a). Over the last four decades, considerable attention has been accorded to the hydrodynamic behavior of spherical particles in different types of non-Newtonian fluids. Most of these efforts, however, have focused on the calculation of what one might call macroscopic hydrodynamic parameters, such as the drag force, effects of the confining walls, and dual interactions between particles themselves as well as between the non-Newtonian complexities and the particles. The bulk of the literature has been critically evaluated and summarized by several authors; for example, see Leal (1979, 1980), Chhabra (1986), Chhabra and Uhlherr (1988), Walters and Tanner (1991), and, most recently, Chhabra (1993a).

In contrast, much less is known about the hydrodynamic behavior of nonspherical-shaped particles in rheologically complex fluids. Significant differences have been predicted and observed, even at the macroscopic level, for small departures from spherical shape and/or from Newtonian flow behavior. Indeed, several unusual phenomena observed with the sedimentation of slender particles and/or clusters of spheres in non-Newtonian systems have been documented in the literature (Joseph and Liu, 1993; Liu and Joseph, 1993; Joseph et al., 1994). It turns out that some of these phenomena, albiet still unexplained, have important ramifications in many engineering processes. In spite of such overwhelming pragmatic significance, most of the literature in this area is not only of recent vintage but also the emerging picture is rather incoherent. This chapter aims to provide a critical appraisal of the pertinent literature. Such a review will not only lead to consolidation of the currently available information but will also facilitate the delineation of the areas warranting further research effort.

II. SCOPE

In general, the scope of this chapter is to review the existing literature on the interplay between nonlinear flow characteristics (shear-dependent viscosity, viscoelasticity, yield stress, etc.) and nonspherical particle shape as encountered both in the sedimentation in quiescent medium as well as in the case of a liquid streaming past a fixed object. The role of confining boundaries is also considered. The main thrust here is on what one might call the macroscopic description of momentum transfer. Finally, although our primary interest here is on the behavior in non-Newtonian systems, reference will frequently be made to the corresponding scene in Newtonian fluids so that some qualitative inferences can be drawn regarding the interactions between particle shape and rheological complexities. Although no consideration is given here to the origins of and to the rheological models used to portray the various kinds of non-Newtonian fluid behavior, interested readers are referred to several outstanding books available on this subject [e.g., among others, see Bird et al. (1987) and Barnes et al. (1989)].

Whereas it is readily recognized that most real materials exhibit varying levels of viscous and elastic properties under different circumstances, it is customary to divide the fluids arbitrarily into the so-called purely viscous (or inelastic or generalized Newtonian fluids, GNFs) and viscoelastic type. Despite the limitations of such a classification, it does provide a convenient initial basis for the presentation of the information on nonspherical