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Invited review

Particle dynamics in viscoelastic liquids

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ABSTRACT

Systems made by particles in viscoelastic liquids are ubiquitous in a variety of industrial and biological applications. Much work has been done in the last half-century in understanding the effect of non-Newtonian properties on the dynamics of the suspended particles. Theoretical predictions, experimental observations and numerical simulations highlighted peculiar phenomena induced by fluid elasticity that dramatically affect the particle motion and patterning.

In this review, the existing literature on the dynamics of non-Brownian particles in viscoelastic fluids is discussed. The main part is focused on the dynamics of rigid particles passively transported in flowing viscoelastic liquids. The available results are classified by increasing level of complexity in terms of hydrodynamic interactions (single-particle problems, binary interactions, multi-body systems) and according to the flow field.

Recent results on soft and active viscoelastic suspensions are also discussed.

Contents

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1. Introduction

Solid particles suspended in flowing liquids are encountered in a huge number of natural, biological and industrial processes. The flow behavior and the rheological properties of these systems are strongly influenced by the presence of the fillers and by their relative motion and spatial distribution. Properties of solid particle suspensions are affected by the size and the shape of the fillers, the solid concentration as well as the suspending fluid properties. Indeed, variations of these characteristics induce important quantitative and qualitative changes in the suspension behavior.

Even for the simplest case of spherical particles in Newtonian liquids, typical non-Newtonian behaviors as viscosity-thinning, shear-thickening and normal stresses in shear flow have been observed at moderate volume fractions [1–3]. This peculiar phenomenology has been attributed to changes in the microstructure due to the interparticle interactions [3].

It is intuitive that the scenario is even more complex when the suspending fluid itself shows a complex rheological behavior. Several industrial and daily-life materials fall in this category, including fiber-reinforced polymers or rubbers, detergents, paints, foods, biological suspensions, just to mention a few [4,5]. Usual non-Newtonian properties such as shear-thinning, elongational thickening, first and second normal stresses may strongly alter the microstructure in flowing suspensions, even at low particle concentrations [6,7]. Needless to say, inhomogeneities in the particle distributions dramatically affect the bulk rheology of the suspension as well as the final properties of the material [8,6,4,9,7].

On the other hand, the peculiar particle dynamics induced by the complex rheology of the suspending matrix can be cleverly exploited to perform operations that would be difficult, if not possible, in Newtonian fluids. As an example, it is worthwhile to mention the emergent use of non-Newtonian fluids in microfluidics to guide the flowing particles in some region of devices for counting, diagnostic and separation applications [10]. Therefore, understanding the dynamics of particles suspended in non-Newtonian fluids is of primary importance to optimize industrial production processes [11,12] and design novel technologies for particle manipulation [13].

The systematic research on this subject started about one-half century ago (see, e.g., the review papers [15,16] and the references therein). Earlier works, mainly reporting macroscopic experimental observations in simple flow cells, highlighted a complex behavior as compared to Newtonian suspensions under similar conditions. Indeed, phenomena like migration and aggregation were observed even at low particle volume concentrations and slow flow conditions. The experimental results were also qualitatively supported by theoretical predictions derived under simplified conditions such as slow and slowly varying flows, and vanishing particle sizes [14–16].

The development of more sophisticated experimental techniques for particle and flow visualization (e.g., particle image velocimetry [17]) allowed the detailed analysis of particle dynamics in a wide range of volume fractions and in complex flow fields. In addition, accurate simulations have been made feasible by the simultaneous growth of computational resources and the development of numerical algorithms able to efficiently solve problems involving non-Newtonian fluids. Simulation results complemented experimental observations giving insights into the investigated phenomena [18]. As a result, several aspects on the particle motion in non-Newtonian media have been clarified, at least for simple particle shapes such as spheres and (to a smaller extent) spheroids.

In this paper, we review the available literature on the dynamics of non-Brownian particles in non-Newtonian fluids. The results discussed in the present work are mainly focused on systems where the suspending liquid exhibits an appreciable degree of elasticity (viscoelastic fluids), which is responsible for the most complex and spectacular phenomena observed in non-Newtonian fluids. The behavior of particles in pseudoplastic or viscoplastic liquids is reviewed elsewhere [5]. Furthermore, we consider systems without interfacial tension, i.e. solid particle suspensions. Comprehensive reviews on Newtonian/viscoelastic drops in non-Newtonian matrices are available in the literature [19–22].

The first part of this review is focused on the mathematical modeling of viscoelastic suspensions. The basic equations governing the particle and fluid dynamics as well as a brief discussion on the typical constitutive equations used in modeling viscoelastic liquids are presented. The dimensionless version of the equations is derived, and the dimensionless relevant parameters are defined.

In the second part, the available results on the dynamics of *rigid* particles in viscoelastic liquids are reviewed. The section is organized by increasing level of complexity in terms of interparticle

Table 1

Flow field	De	Re	G	β	a_r	Relevant dynamics	Section
Single-particle							
Shear	>0	~0	0	0	1	Rotation	4.1.1
Shear	>0	~0	0	0	>1	Rotation/orientation	4.1.2
Shear	>0	~0 >0	0	>0	1	Migration	4.2.1
Couette	>0	~0	0	>0	1	Migration	4.2.2
Poiseuille	>0	~0 >0	0	>0	1	Migration	4.2.3
Two-particles							
Sedimentation	>0	~0	>0	0	1	Aggregation	5.1
Shear	>0	~0	0	0 >0	1	Passing/tumbling/returning motion	5.2
Poiseuille	>0	~0	0	>0	1	Repulsion/attraction	5.3
Three-particles							
Sedimentation	>0	~0	>0	0	1	Aggregation	6.1
Shear	>0	~0	0	0 >0	1	Passing/repelling motion	6.1
Poiseuille	>0	~0	0	>0	1	Repulsion/attraction	6.1
Multi-particles							
Sedimentation	>0	~0	>0	0	1	Aggregation/stratification	6.2
Shear	>0	~0	0	0 >0	1	Chaining	6.3