2 Geophysical Aspects of Non-Newtonian Fluid Mechanics

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2.1 Introduction

Non-Newtonian fluid mechanics is a vast subject that has several journals partly, or primarily, dedicated to its investigation (Journal of Non-Newtonian Fluid Mechanics, Rheologica Acta, Journal of Fluid Mechanics, Journal of Rheology, amongst others). It is an area of active research, both for industrial fluid problems and for applications elsewhere, notably geophysically motivated issues such as the flow of lava and ice, mud slides, snow avalanches and debris flows. The main motivation for this research activity is that, apart from some annoyingly common fluids such as air and water, virtually no fluid is actually Newtonian (that is, having a simple linear relation between stress and strain-rate characterized by a constant viscosity). Several textbooks are useful sources of information; for example, [1,2,3] are standard texts giving mathematical and engineering perspectives upon the subject. In these lecture notes, Ancey’s chapter on rheology (Chap. 3) gives further introduction.

Non-Newtonian fluids arise in virtually every environment. Typical examples within our own bodies are blood and mucus. Other familiar examples are lava, snow, suspensions of clay, mud slurries, toothpaste, tomato ketchup, paints, molten rubber and emulsions. Chemical engineers, and engineers in general, are faced with the (often considerable) practical difficulties of modelling a variety of industrial processes involving the flow of some of these materials. Consequently, much theory has been developed with this in mind, and our aim in this review is to guide the reader through some of the developments and to indicate how and where this theory might be used in the geophysical contexts.

2.2 Microstructure and Macroscopic Fluid Phenomena

Most non-Newtonian fluids are characterized by an underlying microstructure that is primarily responsible for creating the macroscopic properties of the fluid. For example, a variety of non-Newtonian fluids are particulate suspensions – Newtonian solvents, such as water, that contain particles of another material. The microstructure that develops in such suspensions arises from particle–particle or particle–solvent interactions; these are often of electrostatic or chemical origin.
A common example of such a suspension is a slurry of kaolin (clay) in water. Kaolin particles roughly take the form of flat rectangular plates with different electrostatic charges on the faces and on the sides; their physical size is of the order of a micron. In static fluid, the plates stack together like a giant house of cards. This structure becomes so extensive that the electrostatic forces that hold the structure together engender a macroscopic effect, namely the microstructure is able to provide a certain amount of resistance to fluid flow [4].

Of course, the image of the kaolin structure within the slurry as a giant house of cards is a gross idealization. Undoubtedly, the kaolin forms an inhomogeneous, defective structure with a variety of length scales. Nevertheless, the important idea is that microstructure can lead to macroscopic observable effects on the flow of the fluid. For the kaolin slurry, we anticipate that microstructure adds to the resistance to flow provided the shearing (rate of deformation) is not too great. However, once the fluid is flowing and shearing over relatively long scales, the microstructure must disintegrate — the house of cards collapses. Thus, for greater shearing (larger rates of deformation), the fluid begins to flow more easily. This macroscopic, non-Newtonian effect of “shear thinning” is well documented and a key effect in suspension mechanics. The crudest model of the phenomenon is to make the fluid viscosity a decreasing function of the rate of strain. In this simple departure from the regular fluid behaviour, one then makes the shear stress a nonlinear function of the strain rate. This is an example of a “constitutive law”; we elaborate further on such laws soon, but first we continue with a brief discussion of other non-Newtonian effects.

If the concentration of kaolin is sufficiently high, the microstructure can provide so considerable a resistance to deformation that material does not flow at all until a certain amount of stress is exerted on the fluid. At smaller stresses, the fluid behaves like an elastic solid, and simply returns to its original state if the applied stress is removed. Above the critical stress, the “yield stress”, the material begins to flow. Materials exhibiting yield behaviour are said to behave plastically, and when they flow viscously after yield, the terminology viscoplastic is often used.

The kaolin–water slurry is what one might call a “pure” form of mud. But, when the mud is less pure, and contains numerous embedded particles, grains or boulders with widely varying sizes (as in most geophysical conditions), the clay particles still form microstructure, with the attendant macroscopic effects. Hence muds are a classic example of a geophysical viscoplastic fluid. But there are also other geophysical materials with microstructure. For example, snow flakes, through a process of partial melting and refreezing, act to form a static coherent structure; this is relevant when considering avalanches, see also Chap. 13. And lava has a microstructure of bubbles and silicate crystals suspended within a hot viscous solvent.

Shear thinning and yield stresses are common effects in particle suspensions, but they are not the only type of non-Newtonian behaviour we can encounter. Another type of behaviour arises in polymeric fluids. Here, the fluid is laced with high molecular weight deformable molecules (polymers), whose length can