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On the Connection Between Kolmogorov Microscales and Friction in Pipe Flows of Viscoplastic Fluids

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Abstract

The present work extends Kolmogorov's micro-scales to a large family of viscoplastic fluids. The new micro-scales, combined with Gioia and Chakaborty's (Phys. Rev. Lett. 96, 044502, 2006) friction phenomenology theory, lead to a unified framework for the description of the friction coefficient in turbulent flows. A resulting Blasius-type friction equation is tested against some available experimental data and shows good agreement over a significant range of Hedstrom and Reynolds numbers. The work also comments on the role of the new expression as a possible benchmark test for the convergence of DNS simulations. The formula also provides limits for the maximum drag reduction of viscoplastic flows.

Keywords: Kolmogorov Microscales, non-Newtonian Fluids, Viscoplastic, Turbulent Friction Factor

1. Introduction

The description of complex fluids and their rheological behavior in a simple and universal mathematical framework is an elusive task. The classical attempt at classifying the known fluids into two different groups, Newtonian or non-Newtonian, has proven to be ineffective, since the term "non-Newtonian" encompasses a wide family of fluids with unrelated physical behavior. Despite this shortcoming, the scientific community has commonly classified complex fluids into three essential groups: purely-viscous, viscoplastic, and viscoelastic (linear and nonlinear). In this work, the scales of Kolmogorov and their relations to the friction coefficient of a large family of turbulent purely-viscous and viscoplastic fluid flows are described. Although these formulations can be seen as the simplest models to describe the behavior of non-Newtonian fluids, they have been commonly used by engineers to describe several processes in the polymer industry, including injection molding, extrusion and pipe flow with heat transfer (see, e.g., [1]).

For the incompressible flow of a Newtonian fluid, the stress tensor is defined as

$$\tau = -\mu\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right) \equiv \mu \mathbf{S},$$

where $\mathbf{S} = \nabla \mathbf{u} + (\nabla \mathbf{u})^{\mathbf{T}}$ is the *rate-of-strain* tensor. There are several models concerning viscoplastic fluid flows. A large family of such models is described by a simple generalization of the Newtonian model, by simply replacing the constant viscosity μ, by a shear-rate dependent viscosity, $\mu \equiv \mu(\dot{\gamma})$, where $\dot{\gamma} \equiv \sqrt{2\mathbf{S} : \mathbf{S}}$ is the second invariant of the *rate-of-strain* tensor. One important example of this family is the Herschel-Bulkley model, described by

$$\tau = \mu(\dot{\gamma})\mathbf{S},$$