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Rapid rheological characterization of a viscoelastic fluid based on spatiotemporal flow velocimetry

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ABSTRACT

A method to characterize viscoelastic fluids in transient shear is proposed based on spatiotemporal flow velocimetry. Particle tracking velocimetry and ultrasound velocity profiling are functionally applied to obtain shear rate and shear strain of a fluid within a Couette system. The ratio of the cylinder radii is set large differently from ordinary Couette systems so that shear stress and shear strain in their designed ranges are available without changing the rotational speed. Simultaneously performing a torque measurement of the rotating cylinder with flow velocimetry, the spatiotemporal fluid response is converted into a triadic relation among shear rate, shear strain, and shear stress. The relationship is graphically represented as a "flow surface" in the three-dimensional parameter space. For an aqueous polyacrylamide solution, the elementary features, such as yield stress, shear wave, and shear-thinning trend, of the viscoelastic fluid reflected in the flow surface are read off. Finally, the experimental flow surface is directly applied for momentum conservation equation to simulate the viscoelastic flow structure as a demonstration.

1. Introduction

Predicting non-Newtonian fluid flows are becoming increasingly important in material processing. In the field of food-process engineering, for example, internal flows of food materials through devices sensitively alters final properties such as taste and texture. Bio-fluids and chemical industries have similar demands in securing flow control. Distinct from Newtonian fluids, the behavior of complex matter cannot be approximated by the Navier–Stokes equations coupled with equation of continuity. Newton's law of viscosity in the Navier–Stokes equations should be replaced with a constitutive relation that describes the relationship between the shear rate and shear stress for each type of material. The relation is called the "flow curve" in rheology as viscosity varies with shear rate. In general, the flow curve is obtainable experimentally using a rheometer. There have been hundreds of articles in material science journals reporting various special features found in the flow curve. By converting the experimental flow curve to an analytical function, flow-predicting simulations become possible upon the closure of the mathematical formulation (conservation of mass and momentum equations) by the constitutive relation that model the flow curve. These concepts in mathematical description are illustrated in Fig. 1(a)–(c). Here the total stress tensor σ involves pressure. The shear stress component, τ, is described separately to be recognized as the main measurement target in the present study.

In regard to fluid engineering, the flow curve is regarded as the kernel of the flow simulation because it dynamically sways the fluid motion in a given geometry. The flow curve usually should be provided before coding the flow simulation software. Material scientists, nevertheless, recognize the flow curve as a macroscopic result of the material development and spend most of the time on the microscopic physics or chemistry occurring within each particular material of interest. An effort that bridges these two disciplines has been historically lacking, but which is increasingly required in the current rapid development of functional materials. For polymeric materials, such an effort is known as the formulation of various models classified into multiple length scales [1–3] from molecular sizes to chained strings that connect up with the continuum. To obtain flow predictions for each material, we need a constitutive equation as input into the numerical schemes that mathematically close the simultaneous differential equations. The multi-scale description of the model, which depends on the material tested, remains unsuitable when coupled with conservation equations. This arises for two reasons: universality of the non-Newtonian flow simulation would not hold for the different materials to test, and the resolution of the computational grid

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Nomenclature

A	local slope of flow surface in the direction of strain
B	local slope of flow surface in the direction of shear rate
c	weight coefficient between shear rate and shear strain
D	distance between two points on the flow surface
De	Deborah number
D_f	diffusion number
f	frequency of periodic deformation
G'	shear storage modulus
G''	shear loss modulus
H	height of the surface of the test fluid
r	radial position
r_i	radial position in discrete form
r_{in}	radius of the inner cylinder
t	time
T	torque acting on the inner cylinder
$u_{i,j}$	circumferential velocity component in discrete form
u_x	velocity component projected on the measurement line of UVP
u_θ	circumferential velocity component
α	local angle of the measurement point against the central axis of the cylinder
γ	shear strain
γ_0	amplitude of shear strain for periodic deformation
$\dot{\gamma}$	shear rate
$\dot{\gamma}_0$	amplitude of shear rate for periodic deformation
δ	loss angle
η	viscosity
λ	relaxation time
ρ	density of fluid
τ_{wall}	wall shear stress on the inner cylinder
τ	shear stress
τ_0	amplitude of shear stress for periodic deformation

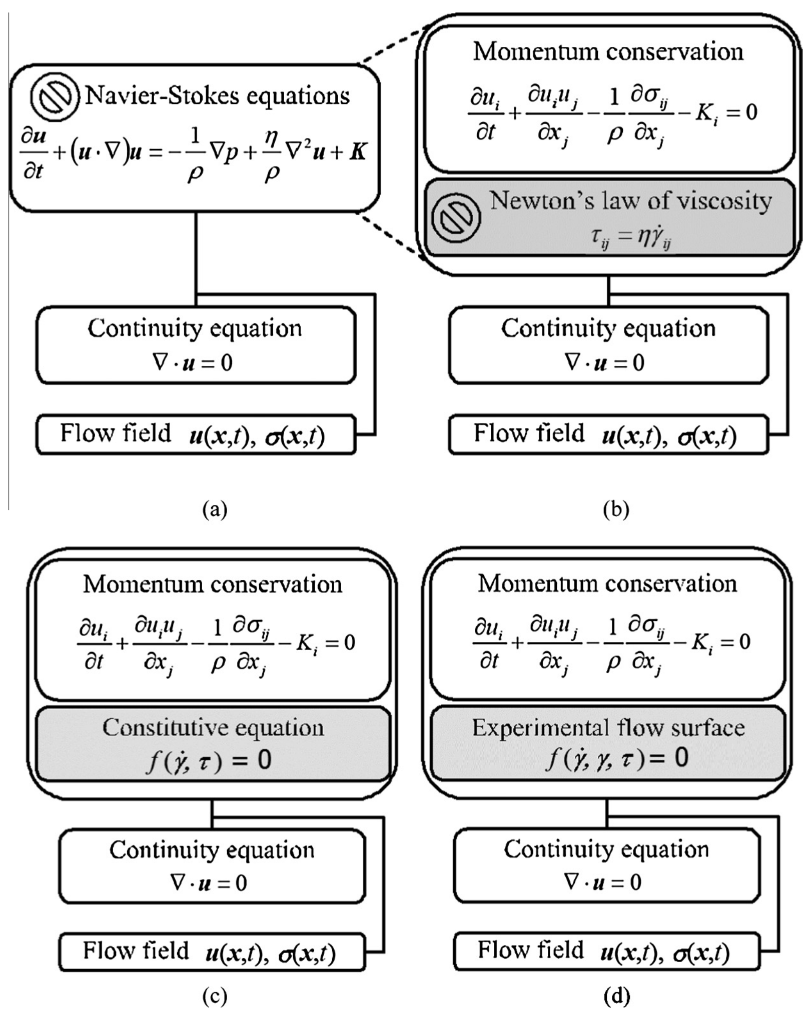

Fig. 1. Schematic of flow prediction for (a) Newtonian fluids with the Navier–Stokes equation, (b) Newtonian fluids with momentum conservation and Newton's law of viscosity, (c) non-Newtonian fluids in conventional way, and (d) non-Newtonian fluids with the proposed method. K stands for external body force per unit volume such as gravity. Because non-Newtonian fluids do not obey Newton's law of viscosity, which is a part of the Navier–Stokes equation, constitutive relations are required to alter Newton's law. The proposed method exploits experimental data instead of constitutive model equations.