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Summary

Division of Energy and Environmental Systems
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On the Macrodynamic Identification of Flow Modulations in non-Newtonian Shear Flows

by Akihide Takano

Fluid mechanics has been established as a discipline describing the transport of momentum and energy through advection phenomena, and many flows considered therein are represented by simple constitutive relations assuming Newtonian fluids. Nonlinear phenomena, typified by turbulence, arise from the advective terms in the governing equations; however, in complex fluids, intrinsic relaxation mechanisms of the fluid itself modulate the flow and generate additional complexity. For instance, in viscoelastic fluids such as surfactant or polymer solutions that exhibit drag reduction, non-Newtonian properties interact with the flow and modify dynamical characteristics associated with advection, leading to diverse nonlinear behaviors. Such modulation of flow appears as an universal phenomenon across a wide range of scales. To understand flow phenomena in complex fluids, it is necessary to quantify the dynamical properties governing modulation, namely how momentum diffusion and transport occur within the flow field. Based on this philosophy, the present study aims to define macroscopic indicators representing momentum diffusion and transport that systematically characterize flow modulation, thereby providing a unified understanding of phenomena ranging from particle sedimentation to turbulent transport. Surfactant solutions, which exhibit turbulent drag reduction and are practically utilized in applications such as the Alaska pipeline and the heating system of Sapporo City Hall, are adopted as representative viscoelastic complex fluids. Chapter I summarizes the research background of these flow modulation phenomena.

In Chapter II, sedimentation of particle clouds in a surfactant solution was investigated using a Hele-Shaw (HS) configuration that realizes quasi-two-dimensional flow field. The solution exhibits viscoelasticity, and wake structures behind particle clouds can exhibit regions of reversed flow and altered vorticity distribution compared with Newtonian fluids. These wake structures are associated with the extensional relaxation time scale of the solution, thereby modulating collective sedimentation behavior. As a consequence, particle clouds repeatedly split and reaggregate while forming streak-like structures. Quantitative image tracking of particle-cloud contours and particle numbers

revealed that the global sedimentation dynamics of particle clouds can be described as a nonlinear diffusion process governed by a logistic equation. The macroscopic diffusion time scale in the surfactant solution is shorter than that in water, suggesting that rapid diffusion arises from cyclic behavior of particle splitting and reaggregation governed by extensional relaxation. These results clearly demonstrate that microscopic viscoelasticity in non-Newtonian fluids modifies macroscopic particle-cloud diffusion processes.

From Chapter III, flow modulation in Taylor-Couette (TC) flow between concentric cylinders is investigated. This flow configuration allows stable realization of various three-dimensional flow states ranging from steady Taylor vortex flow with a single wavelength to fully turbulent flow with smaller scale fluctuations. Furthermore, since the flow is closed in the azimuthal direction, modulation phenomena induced by complex fluids can be represented by statistically steady quantities. First, a novel methodology was proposed to quantify viscoelastic properties of surfactant solutions under simple shear. While low-viscosity fluids such as water can be evaluated using TC-type geometries connected to the commercial rheometer, surfactant solutions often exhibit poor reproducibility because localized entanglement of polymer-like structures induced by centrifugal effects, known as shear-induced structures (SIS), develops within the flow. In Section III.1, a turbulent pre-conditioning method was proposed, in which high shear is applied prior to measurement to promote uniform SIS formation throughout the test fluid. By analyzing the relationship between energy input during pre-conditioning and subsequent local structuring, it was shown that sufficient energy injection by shear is necessary to suppress localized SIS formation. The proposed method enables reproducible viscoelastic measurements of surfactant solutions with homogeneous SIS formation. Moreover, because shear induces elastic structures and alters material properties during turbulent transition in surfactant solutions, systematic studies of transition processes have been scarce compared with other viscoelastic fluids. Therefore, Section III.2 presents a systematic investigation of elasto-inertial turbulence transition in surfactant solutions using this methodology as a foundational technique. Under initial conditions independent of flow history, azimuthal flow structures were visualized while high-precision shear stress measurements were conducted. By systematically varying the Weissenberg and Reynolds numbers governing elasto-inertial turbulence, the relationship between shear stress variation and spatial wavenumber was examined, revealing that effective momentum transport represented by shear stress is modulated depending on spatial flow structures formed through elastic–inertial interactions.

Turbulence modulation observed in complex fluids thus originates from the modification of inertia-driven momentum transport by locally shear-dependent rheological properties. The averaged momentum transfer generated by turbulent fluctuations is commonly described as Reynolds stress. In classical fluid mechanics dealing with Newtonian fluids, eddy viscosity has long been discussed as a model parameter for estimating Reynolds stress. However, conventional physical models of eddy viscosity rely on Newtonian energy cascade, and no established method exists for estimating eddy viscosity applicable to complex fluids. Focusing on the fact that spatial structures of mean velocity distributions reflect local Reynolds stresses, eddy viscosity was redefined here as a momentum diffusion indicator corresponding to averaged velocity gradients. Section IV.1 proposes a novel experimental method for directly measuring eddy viscosity. In this method, the mean flow advection equation is solved using ultrasonic velocity measurements, and eddy viscosity is evaluated as a residual term. Validation measurements conducted for Newtonian fluids enabled discussion of physical interpretations of measured eddy viscosity through comparison with classical turbulence scaling laws. Furthermore, Section IV.2 introduces a modal decomposition-based eddy viscosity analysis, in which eddy viscosity is decomposed according to flow structures. TC flow contains characteristic coherent structures observed in shear turbulence, such as rolls, streaks, and their wave-like modulations. Recent studies have discussed mechanisms of momentum transfer among these structures. In this section, advection equations were derived for modes composing each mean flow (mean, roll, and streak modes), and momentum exchange among coherent structures was evaluated through effective eddy-viscous diffusion associated with mean velocity gradients of each mode. This approach interprets nonlinear amplification mechanisms exchanged among components of the self-sustaining process in terms of turbulent diffusion expressed as eddy viscosity.

Chapter V applies this methodology to viscoelastic turbulence modulation in surfactant solutions. Since the target flow field arises from bidirectional interactions between elasticity and inertia, viscoelastic stress terms were incorporated into the mean-flow advection equation to reflect viscoelastic effects in the analysis. As a result, it was evaluated that, in regions where Reynolds stress decreases due to elastic–inertial interactions, eddy viscosity correspondingly decreases while balancing the increase in viscoelastic stress contributions.

Through this study, an experimental and theoretical framework was presented for systematically understanding dynamical properties of complex fluids from the perspective of averaged diffusion and transport rooted in various scales. By traversing flow systems from quasi-two-dimensional HS flows to fully three-dimensional TC flows while focusing on dynamical diffusion and transport, interactions between relaxation mechanisms inherent in non-Newtonian fluids and flow dynamics were quantitatively characterized. The present work demonstrates that phenomena ranging from particle sedimentation to turbulent transport can be consistently interpreted through the common concept of scale-dependent diffusion, thereby suggesting the possibility of describing universal principles of flow across different scales.