

Preface

This monograph together with its complimentary volume [Siginer, D. A., *Stability of Non-linear Constitutive Formulations for Viscoelastic Fluids*, Springer, New York, 2014] in this series is an attempt to give an overall comprehensive view of a complex field, only 60 or so years old, still far from being settled on firm grounds, that of the dynamics of viscoelastic fluid flow and suspension flow in tubes. The monograph on “Stability of Non-linear Constitutive Formulations for Viscoelastic Fluid Media” covers the development of constitutive equation formulations for viscoelastic fluids in their historical context together with the latest progress made, and this volume covers the state-of-the-art knowledge in predicting the flow of viscoelastic fluids and suspensions in tubes highlighting the historical as well as the most recent findings. Most if not all viscoelastic fluids in industrial manufacturing processes flow in laminar regime through tubes, which are not necessarily circular, at one time or another during the processing of the material. Laminar regime is by far the predominant flow mode for viscoelastic fluids encountered in manufacturing processes, and it is extensively covered in this monograph. Turbulent flow of dilute viscoelastic solutions is a topic which has not received much attention except when related to drag reduction. For particle-laden flows there are very interesting developments in both laminar and turbulent regime, and they are duly covered. It is critically important that the flow of non-linear viscoelastic fluids and suspensions in tubes can be predicted on a sound basis, thus the *raison d'être* of this volume. As flow behavior predictions are directly related to the constitutive formulations used, this volume relies heavily on the volume on [Siginer, D. A., *Stability of Non-linear Constitutive Formulations for Viscoelastic Fluids*, Springer, New York, 2014].

The science of rheology defined as the study of *the deformation and flow of matter* was virtually single-handedly founded and the name invented by Professor Bingham of Lafayette College in the late 1920s. Rheology is a wide encompassing science which covers the study of the deformation and flow of diverse materials such as polymers, suspensions, asphalt, lubricants, paints, plastics, rubber, and biofluids, all of which display non-Newtonian behavior when subjected to external

stimuli and as a result deform and flow in a manner not predictable by Newtonian mechanics.

The development of rheology, which had gotten to a slow start, took a boost during WWII as materials used in various applications, in flame throwers, for instance, were found to be viscoelastic. As Truesdell and Noll famously wrote [Truesdell, C. and Noll, W., *the Non-Linear Field Theories of Mechanics*, 2nd ed., Springer, Berlin, 1992] “By 1949 all work on the foundations of Rheology done before 1945 had been rendered obsolete.” In the years following WWII, the emergence and rapid growth of the synthetic fiber and polymer processing industries, appearance of liquid detergents, multigrade oils, non-drip paints, and contact adhesives, and developments in pharmaceutical and food industries and biotechnology spurred the development of rheology. All these examples clearly illustrate the relevance of rheological studies to life and industry. The reliance of all these fields on rheological studies is at the very basis of many if not all of the amazing developments and success stories ending up with many of the products used by the public at large in everyday life.

Non-Newtonian fluid mechanics, which is an integral part of rheology, really made big strides only after WWII and has been developing at a rapid rate ever since. The development of reliable constitutive formulations to predict the behavior of flowing substances with non-linear stress–strain relationships is quite a difficult proposition by comparison with Newtonian fluid mechanics with linear stress–strain relationship. The latter does enjoy a head start of two centuries tracing back its inception to Newton and luminaries like Euler and Bernoulli. With the former the non-linear structure does not allow the merging of the constitutive equations for the stress components with the linear momentum equation as it is the case with Newtonian fluids ending up with the Navier–Stokes equations. Thus, the practitioner ends up with six additional scalar equations to be solved in three dimensions for the six independent components of the symmetric stress tensor. The difficulties in solving in tandem this set of non-linear field equations, which may involve both inertial and constitutive non-linearities, cannot be underestimated. Perhaps equally importantly at this point in time in the unfolding development of the science, we are not fortunate enough to have developed a single constitutive formulation for viscoelastic fluids, which may lend itself to most applications and yield reasonably accurate predictions together with the field balance equations. The field is littered with a plethora of equations, some of which may yield reasonable predictions in some flows and utterly unacceptable predictions in others. Thus, we end up with classes of equations for viscoelastic fluids that would apply to classes of flows and fluids, an ad hoc concept at best that hopefully will give way one day to a universal equation, which may apply to all fluids in all motions. In addition the stability of these equations is a very important issue. Any given constitutive equation should be stable in the Hadamard and dissipative sense and should not violate the basic principles of thermodynamics.

Dynamics of tube flow of non-Brownian suspensions and its underpinning field turbulent motion of linear (Newtonian) fluids shows interesting similarities with the flow of viscoelastic fluids in that the secondary flows of viscoelastic fluids in

laminar flow driven by unbalanced normal stresses have a counterpart in the turbulent motion of linear fluids in straight tubes of non-circular cross section and in the laminar motion of particle-laden linear fluids. The latter secondary flows are driven by normal stresses due to shear-induced migration of particles. This is a new topic of hot research thrust given its implications in applications. The direction of these normal stresses is opposite of those present in the flow field of a viscoelastic fluid. In fact the tying thread among these seemingly different motions is that all are driven by normal stresses. The turbulent flow of linear fluids is known to have a transversal field due to the anisotropy of the Reynolds stress tensor in non-circular cross sections which entails unbalanced normal Reynolds stresses in the cross section perpendicular to the axial direction. Secondary field also exists in the turbulent flow of linear fluids in circular cross sections if the symmetry is somehow broken due, for example, to unevenly distributed roughness on the boundary, which would again trigger anisotropy of the Reynolds stress tensor. It is not possible to develop a good understanding of the mechanics of the secondary field both in laminar and turbulent motion of particle-laden fluids without a clear grasp of the underlying mechanics of the turbulent secondary field of homogeneous linear fluids. Thus a complete review of both is presented including interesting constitutive similarities with viscoelastic fluids which do arise when certain non-linear closure approximations are made for the anisotropic part of the Reynolds stress tensor.

The impact of the secondary flows on engineering calculations is particularly important as turbulent flows in ducts of non-circular cross section are often encountered in engineering practice. Some examples are flows in heat exchangers, ventilation and air-conditioning systems, nuclear reactors, impellers, blade passages, aircraft intakes, and turbomachinery. If neglected significant errors may be introduced in the design as secondary flows lead to additional friction losses and can shift the location of the maximum momentum transport from the duct centerline. The secondary velocity depends on cross-sectional coordinates alone and therefore is independent of end effects. It is only of the order of 1–3 % of the streamwise bulk velocity, but by transporting high-momentum fluid toward the corners, it distorts substantially the cross-sectional equal axial velocity lines; specifically it causes a bulging of the velocity contours toward the corners with important consequences such as considerable friction losses. The need for turbulence models that can reliably predict the secondary flows that may occur in engineering applications is of paramount importance.

Efforts have not been spared to be thorough in the presentation with commentaries about the successes and failures of each theory and the reasons behind them. The link between different theories and the naturally unfolding succession of theories over time borne out of the necessity of better predictions as well as the challenges in the field at this time are given much emphasis at the expense of a detailed in-depth development of various theories. This book provides a snapshot of a fast developing topic and a bridge connecting new research results with a timely and comprehensive literature review. For a detailed in-depth exposition of anyone subject included in this book, the reader is referred to the extensive reference list.

The responsibility for any mistakes and misquotes that may have crept up into the text in spite of extensive checking remains solely with the author.

As a final note we remark that the intention of this book is to emphasize the common features of and the links between three seemingly different fields, tube flow of viscoelastic fluids, turbulent tube flow of Newtonian fluids, and tube flow of non-colloidal suspensions, and to help bridge the mechanics of all three. The notation used in the literature by the practitioners of all three fields is somewhat different and is kept the same in this book not to create confusion with the existing literature. For instance, the extra stress in viscoelastic fluid flow is denoted by \mathbf{S} , whereas the Reynolds stress in the turbulent flow of Newtonian fluids, which is essentially an extra stress as well, is denoted by $\boldsymbol{\tau}$. In the same vein the suspension stress is indicated by $\boldsymbol{\Sigma}$. The symbols are carefully defined wherever they appear in the text.

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