Journal of Computational Science 29 (2018) 70–80

Contents lists available at ScienceDirect

Journal of Computational Science

journal homepage: www.elsevier.com/locate/jocs

An N-parallel FENE-P constitutive model and its application in large-eddy simulation of viscoelastic turbulent drag-reducing flow

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ARTICLE INFO

Article history:
Received 16 August 2018
Received in revised form 25 September 2018
Accepted 29 September 2018
Available online 5 October 2018

Keywords:
N-parallel FENE-P model
Viscoelastic fluid
Multiple relaxation times
Apparent viscosity
Large-eddy simulation

ABSTRACT

In this paper, an N-parallel FENE-P constitutive model based on multiple relaxation times is proposed, it can be viewed as a simplified version of the multi-mode FENE-P model under the assumption of identical deformation rate. The proposed model holds the merit of multiple relaxation times to preserve good computational accuracy but could reduce the computational cost, especially in the application of high-fidelity numerical simulation of viscoelastic turbulent drag-reducing flow. Firstly the establishment of N-parallel FENE-P model and the numerical approach to calculate the apparent viscosity are introduced. Then the proposed model is compared with the experimental data and the conventional FENE-P model in estimating rheological properties of two common-used viscoelastic fluids to validate its performance. This work is an extended version of our ICCS conference paper [1]. To further judge the performance of the proposed FENE-P model in complex turbulent flows, the extended application of the proposed model in large-eddy simulation of viscoelastic turbulent drag-reducing channel flow is carried out.

1. Introduction

In 1948, Toms [2] first reported an interesting phenomenon that adding a little bit of additive, such as some kinds of polymers, into the turbulent flow would induce a drag reduction (DR) in the 1st International Rheology Congress, it was later called turbulent DR effect or Toms' effect. From 1950 to now, as two kinds of successful turbulent drag reducers, the researches on turbulent DR mechanism and industrial applications of the polymer and surfactant have attracted a multitude of scholars' attention all over the world. Among the popular research approaches, numerical simulation has become a powerful tool to get insight into the DR mechanism of the viscoelastic fluid accompanying with rapid developments in mathematical modeling and computer science in recent years. However, distinguishing from the Newtonian fluid, the viscoelastic fluid shows complicated rheological properties and elastic effect. It is a prerequisite to establish a constitutive model that describing the quantitative relation between elastic stress and strain in numerical simulations of viscoelastic turbulent drag-reducing flow. In general, the upper convected Maxwell (UCM) model [3], Oldroyd-B model [4,5] and Giesekus model [6] as well as the FENE-P model [7] are commonly-used constitutive models in a large number of studies. For the desirable performance to represent the shear-thinning property compared with the UCM and Oldroyd-B models, the Giesekus and FENE-P models have been applied widely. Especially in the FENE-P model the deformation is assumed to be finitely extensible nonlinear, which matches the physical process well.

It is well known that the rheological properties and turbulent DR effect are closely related to the microstructures (such as the long-chain structure in the polymer solution, network structure in surfactant solution, etc.) formed in viscoelastic fluids. Therefore, it is necessary to delve into the validity of the constitutive model from the deformation of microstructures. For the polymer solution, as the Fig. 1(a) shows, the long-chain structure would exert dynamic deformation under the shear effect in flow, sometimes they would tangle with each other [8]. Different from the polymer solution, the DR effect of surfactant solution depends on the micelles which are composed of small surfactant molecules. As illustrated in Fig. 1(b), the spherical micelles, rod-like micelles and network structures would be formed in sequence with the

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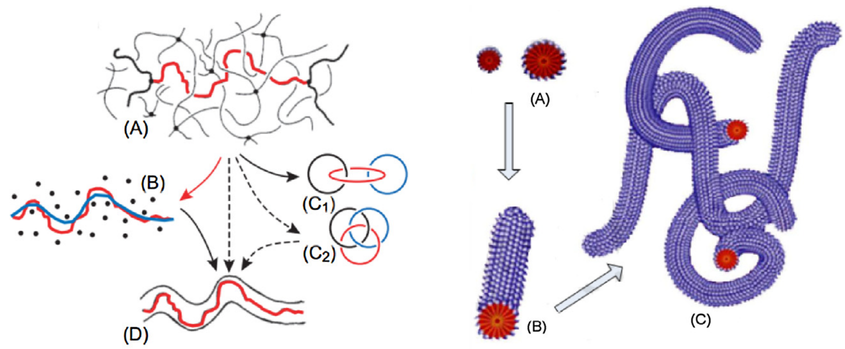
https://doi.org/10.1016/j.jocs.2018.09.016
1877-7503/



(a) High-molecular polymer solution (b) Surfactant solution

Fig. 1. Schematics of microstructures formed in two viscoelastic fluids.

increase of the surfactant concentration under shear effect in flow, accompanying with dynamic deformations of microstructures [9]. From above all, it is evident to see that various deformations of microstructures will take place under the shear effect in viscoelastic fluid. The difficulty to deform can be measured by the relaxation time, it reflects the elastic effect strength of the viscoelastic fluid and is a significant parameter in the constitutive model. For the real viscoelastic fluid, the relaxation time has a wide range of scales (called spectral/multiple relaxation times) due to the anisotropy caused by various deformations and configurational states in the shear flow. In theoretical and experimental studies of the DR effect, however, the multiple relaxation times are always simplified as single relaxation time because of the extra computational cost and sophisticated analysis when multiple relaxation times are considered. Correspondingly, the commonly-used constitutive models mentioned above are characterized by only a single relaxation time, which is inconsistent with the real physical process apparently. It is the main reason that results in deviations between the theoretical, experimental and numerical studies of DR mechanism of viscoelastic turbulent flow.

Based on the deformation characteristics of the microstructures in viscoelastic fluid, though the FENE-P model has been illustrated to accurately describe the deformation during unravelled and extended states of the polymer [10–14] and is sufficient for steady flow [15], it is apparent that the traditional FENE-P model with single relaxation time is incapable of accurately characterizing the anisotropy of the deformations or the oscillatory dynamic viscoelasticity. To improve this shortcoming, the multi-mode FENE bead-spring chain model considering multiple relaxation times was proposed and applied to provide a satisfactory description of the polymer dynamics in flows involving a wide range of polymer configurational states [10,11,13,16]. However, these models are rarely used in practice due to their prohibitive computational cost. This limitation would be highlighted especially in the direct numerical simulation (DNS) or large-eddy simulation (LES) of viscoelastic turbulent drag-reducing flow with additives (drag reducer) because extra FENE-P models need to be solved in the simulation.

Therefore, there is a need to develop new or improved multi-mode models which can mimic the dynamics predicted by the FENE chain at a more affordable computational cost. In this study, a simplified multi-mode FENE-P model that we call N-parallel FENE-P model is put forward. The proposed model holds the multiple relaxation times but could relieve the computational burden under the assumption of identical deformation rate in numerical applications. Although this is not the first attempt to empoly the idea of multiple relaxation times (multi-mode) to describe the complex rheological behaviors of viscoelastic fluids, the problem we want to address in this paper stems from the high-fidelity numerical simulation (such as DNS, LES) of viscoelastic turbulent drag-reducing flow, which has high requirement on the accurate representation of the rheological properties (especially the apparent viscosity) of the viscoelastic fluid. However, it is always contradictory because the additional computational cost would be introduced if the multi-mode FENE-P model is applied. Therefore, it does make sense to improve the multi-mode FENE-P model to gain a good balance between the computational cost and computational accuracy in the simulation. The contribution of this work mainly focuses on two aspects: firstly we propose a simple N-parallel FENE-P model to capture the complex rheological behaviors of viscoelastic fluid with small number mode as least as possible (it needs at least two modes) under the assumption of identical deformation rate for each mode. Fortunately, it is validated with the experimental data and the traditional FENE-P model that our proposed N-parallel FENE-P model is already powerful enough with two contrasted relaxation timescales. Then the double-parallel FENE-P model is applied to the LES of viscoelastic turbulent drag-reducing channel flow. To the best of our knowledge, this is the first attempt that the multi-mode type FENE-P model is employed to the LES study of anisotropic turbulent drag-reducing flow with polymer drag reducer, because for the LES of viscoelastic fluid, the construction of the sub-grid scale (SGS) model is still far from its maturity.

The remainder of this paper is organized as follows. In Section 2, we introduce the establishment of the N-parallel FENE-P constitutive model. The numerical approach to compute the apparent viscosity is briefly presented in Section 3. The validation of the proposed N-parallel FENE-P model with experimental data and traditional FENE-P model is illustrated in Section 4. In Section 5, we apply the double-parallel FENE-P model with two relaxation timescales to the LES of viscoelastic turbulent drag-reducing channel flow. The concluding remarks of this work are summarized in Section 6.

2. Establishment of the N-parallel FENE-P constitutive model

The core idea of the proposed N-parallel FENE-P constitutive model is to put total number N branching FENE-P models in parallel, which enables it holds the multiple relaxation times but could reduce the computational burden in numerical simulations because only one group of deformation rate tensor need to solve. The proposed FENE-P model can describe the rheological behaviors of viscoelastic fluid and characterize the anisotropy of microstructure deformations more accurately. In the following text, the establishment of the improved FENE-P type model is introduced in detail.

To get insight into the rheological properties of the viscoelastic fluid from the microcosmic viewpoint, Bird et al. [7] modeled the polymer macromolecules by using a discrete-element model with the finitely extensible nonlinear elastic (FENE) characteristic,