Viscoelastic flow in porous media – a web of sticky strands

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Résumé

The flow of polymer solutions through porous media is a rich problem in fluid mechanics, combining the complexity of flows through porous structures with the viscoelasticity of the fluid. Such flows can display peculiar behaviors, including: instabilities at low Reynolds numbers and "elastic turbulence"; a strong localization of polymeric stress in specific zones at pore-scale; or an increase of flow resistance at Darcy-scale, even for a fluid that is shear-thinning in a rotational rheometer. Despite continuous efforts, a clear picture of the small-scale mechanisms involved and their link with larger scale phenomena are still lacking.

To better understand this problem, we first developed a code to simulate the flow of viscoelastic fluids through model porous structures (1). This code is based upon a new staggered projection scheme for viscoelastic flows, with some unique properties. It shows good accuracy, even for relatively large Weissenberg numbers (ratio of elastic to viscous forces). It verifies important mathematical properties – the conformation tensor remains symmetric positive definite and the space semi-discretization is consistent with a free-energy estimate. It is well suited to high-performance computing (HPC) and can be readily used for a variety of viscoelastic constitutive laws such as Oldroyd or FENE-type models. It is also implemented for HPC in the CALIF3S open-source platform developed at the Institut de Radioprotection et de Sûreté Nucléaire (IRSN).

Our first step was to simulate steady-state flows through 2D arrays of cylinders (2). We showed that localized zones of large polymeric stress, known as birefringent strands, guide the flow of an Oldroyd-B fluid through the porous structures. We found that these strands form a web (see Figure) through the porous structure that generates a complete reorganization of the flow with an increase of stagnation zones, a reinforcement of preferential paths and a splitting of flow channels. We also found that this reorganization is the source of an increase in global dissipation that can be directly linked with the increase of flow resistance. Our results demonstrate that the birefringent strands – not the elongational viscosity – control the flow of viscoelastic fluids through porous media and that the increase of flow resistance can occur even at steady-state, before the transition to elastic turbulence.

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Recent microfluidic experiments (3,4) have studied the transition to unsteady flow in 2D lattices of hexagonal cylinders and have evidenced complex spatiotemporal fluctuations. By randomly displacing the cylinders from their original position, (3) also suggest that disorder suppresses the instability. But (4) found a counterexample showing that disordering the structure can also promote the instability. They propose that the parameter controlling this phenomenon is the number of stagnation points on the surface of the cylinders that are accessible to the main flow, with the idea that stagnation points act as a source of polymeric stress and thus lead to the instability. In geometries where successive obstacles can screen each other, the development of the instability may be delayed. Here, we will detail the nonlinear dynamics of these instabilities using HPC simulations of the flow. We will show that different regimes develop that explain the experimental observations. We will also show that these regimes are all controlled by the dynamics of "sticky" birefringent strands, thus demonstrating that these strands are the key to understanding both steady and unsteady flows of viscoelastic fluids through porous media.

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