Tumbling in an extensional flow

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Polymers exhibit a complex behaviour even in simple laminar flows. According to the geometry of the flow, polymers can indeed stretch, fold, kink, and thus display a variety of conformations [1]. In a shear flow, the dynamics of a flexible polymer is dominated by an aperiodic end-over-end tumbling motion [2,3,4]. The polymer spends most of the time aligned with the direction of shear and occasionally reverses its orientation because of the combined action of the flow and of thermal fluctuations. The dumbbell model, which simply consists of two beads joined by an elastic spring, captures the main properties of the tumbling motion of flexible polymers in a shear flow [5,6]. In particular, the distribution of the time intervals separating two reversals has an exponential tail with a time scale decreasing as a power-law of the Weissenberg number Wi. Semi-flexible polymers also undergo end-over-end tumbling when immersed in a shear flow [7]. The phenomenon of polymer tumbling is thus commonly associated with shear flows.

We address the question of whether tumbling can also exist in stretching-dominated flows. In an extensional flow, the dumbbell model yields a trivial temporal dynamics : it simply aligns with the stretching direction of the flow, while its extension fluctuates around a value that depends on Wi. A much richer dynamics is obtained by considering the simplest model of semi-flexible polymer, namely the trumbbell model, which consists of three beads joined by two rigid connectors and of an elastic hinge at the central bead [8]. The trumbbell model has been used to study the low-frequency behaviour of stiff macromolecules and the viscoelastic properties of suspensions of such macromolecules [9]. We show that the mere inclusion of one bending mode in the polymer model yields a random end-over-end tumbling motion in an extensional flow. The trumbbell spends a significant amount of time extended and oriented along the stretching direction of the flow ; occasionally, a favourable sequence of thermal fluctuations make the trumbbell fold, reverse its orientation and unfold. The analysis of the statistics of this tumbling-through-folding motion reveals a fundamental difference between extensional flows and shear flows. In an extensional flow, indeed, the mean time separating two reversals grows with Wi, and the growth is exponential. This phenomenon is explained by performing a stability analysis of the dynamical system describing the configuration of the trumbbell and by applying the large deviation theory to it.

Références

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