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EFFECTS OF INTERPARTICLE FRICTION ON THE RHEOLOGY OF FIBRE SUSPENSIONS

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ABSTRACT

Controlling the rheology of fibre suspensions is of critical importance in papermaking and composites processing; the spatial distribution and orientation distribution of fibres are retained in the final structure of the produced materials, significantly affecting their performance in end-use.

In this work, straight, rigid, non-Brownian fibres flowing in a linear shear gradient of a Newtonian fluid medium is investigated. It is also assumed that the particle size and shear rate is great enough, so that colloidal forces become negligible relative to hydrodynamic forces. The effects of the fibre aspect ratio r_{p}, the dimensionless concentration nL^3, and the coefficient of friction μ_{f}, on the apparent viscosity of the suspension, and the tendency of the fibres to agglomerate were investigated. Here, n is the number concentration of fibres, and L is the fibre length.

Lindström and Uesaka [1,2] proposed a fibre suspension model, in which the fibres are modelled as chains of fibre segments, whose motion is governed by Newton's second law. The motion of the fluid medium is calculated from the three-dimensional Navier–Stokes equations. The two-way coupling between phases is taken into account by enforcing momentum conservation between the fibres and the fluid phase. Long-range and short-range hydrodynamic interactions are included in the model, as well as normal and frictional interparticle forces. The model is thus well-suited for investigating the present parameter space.

Simulations were carried out on a box-shaped domain. The boundary conditions of two opposing solid walls were set to model lateral wall motion in opposite directions. The other boundary conditions were periodic. The initial fibre orientation distribution and spatial distribution were isotropic. The apparent viscosity, the normal stress differences, and a measure of the flocculation were monitored. The viscosity and normal stress differences were computed directly from the simulated stresses of the suspension. The intensity of flocculation was defined as $P_L = s_L^2(nL^3)/\bar{n}L^3$. Here, $s_L^2(\ldots)$ denotes the variance of a quantity over many volume elements L^3, and $\bar{n}$ is the mean number concentration of fibre centroids. For a uniform random spatial distribution, we have $P_L = 1$.

Previous numerical investigations [2,3] have indicated that friction may affect the stresses of the suspension and the tendency of fibre aggregation. In this study, the parameter three-space $r_{\mathrm{p}} \times nL^3 \times \mu_{\mathrm{f}}$ is systematically investigated in the non-concentrated regime $nL^3 < r_{\mathrm{p}}$. An example of the evolution of the fibre configuration has been illustrated in Fig. 1. The fibre orientation distribution is initially isotropic. The fibres rotate almost in-phase toward the plane perpendicular to the gradient direction.

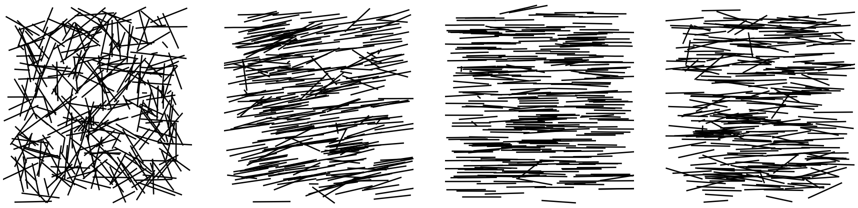

Figure 1: Evolution of the fibre configuration with the applied shear γ. Here, $r_\mathrm{p} = 30$, $nL^3 = 4$, and $\mu_\mathrm{f} = 0$.

Eventually, the orientation distribution approaches a steady state for which the rheological properties are measured and time-averaged.

The intensity of flocculation was most significantly dependent on the dimensionless concentration nL^3. It was observed in some instances that P_L approached a value less than one, indicating the presence of dispersive mechanisms. The intensity of flocculation increased as nL^3 increased. It was not possible to observe any strong effect of friction on fibre agglomeration in the investigated range $\mu_\mathrm{f} \in [0, 1]$.

An approximately linear dependence of the first normal stress difference on the coefficient of friction was observed at all investigated concentrations and aspect ratios. It was found that the first normal stress difference is proportional to the number of fibre collisions—that is mechanical interactions—occurring in the suspension per unit volume and unit time. This rate p_c is $\mathcal{O}(n^2L^6)$. Each collision locally disturbs the fibre orientation distribution; the greater the coefficient of friction, the greater the magnitude of the disturbance. These disturbances, in turn, determine the first normal stress difference in accordance with the existing theories of the stress contribution for the fibre fraction [4,5].

The apparent viscosity is $nL^3/r_\mathrm{eq} \ln(2r_\mathrm{p})$, where r_eq is the equivalent aspect ratio of cylindrical particles. It was shown that mechanical interactions enters the expression for the apparent viscosity through a term proportional to $f(\mu_\mathrm{f})p_\mathrm{c}$, where $f(\mu_\mathrm{f})$ is independent of fibre aspect ratio and concentratuin. This mechanism of mechanical interactions allows for a qualitative description of the apparent viscosity in the transition region between the dilute and the concentrated regimes, without the introduction of slender body assumptions.

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