On the structure and rheology of suspensions of spherical capsules

O. Aouane[1,*], A. Scagliarini[2,3], M. Sega[1], and J. Harting[1,4,5]

1. Forschungszentrum Jülich GmbH, Helmholtz Institute Erlangen-Nürnberg for Renewable Energy (IEK-11), Nuremberg, Germany
2. Istituto per le Applicazioni del Calcolo 'M. Picone', IAC-CNR, Rome, Italy
3. INFN, sezione Roma 'Tor Vergata', Rome, Italy
4. Department of Chemical and Biological Engineering and Department of Physics, Friedrich-Alexander-University Erlangen-Nürnberg, Nuremberg, Germany
5. Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands

*o.aouane@fz-juelich.de

HI ERN Helmholtz Institute Erlangen-Nürnberg

Abstract

We investigate the rheology of strain-hardening spherical capsules, from the dilute to the concentrated regime under a confined shear flow using three-dimensional numerical simulations based on the lattice Boltzmann method (LBM) coupled with a finite element method (FEM) for the particles through the immersed boundary method (IBM). We consider the effect of capillary number (C_a), volume fraction (ϕ) and membrane inextensibility (C) on the particle deformation and on the effective viscosity of the suspension.

The suspension of capsules exhibits a shear-thinning character that becomes more pronounced as the volume fraction increases. The mean deformation and the relative viscosity of the capsules show a universal behavior when considering the subtle interplay between the C_a, ϕ, and C.

Simulation setup

- Two planar walls in the z-axis.
- Biperiodic along x- and y-axis.
- Shear flow: Zou & He B.C.

- Particles: triangular mesh w/ 1280 faces and 642 nodes.
- Membrane model: Skalak hyperelastic law.

Relevant parameters:

- $C \in [10^{-3}; 7.5\times10^{3}]$
- $\phi \in [10^{-3}, 0.5]$
- $C_a \in [0.1, 1]$
- $R_e < 0.03$

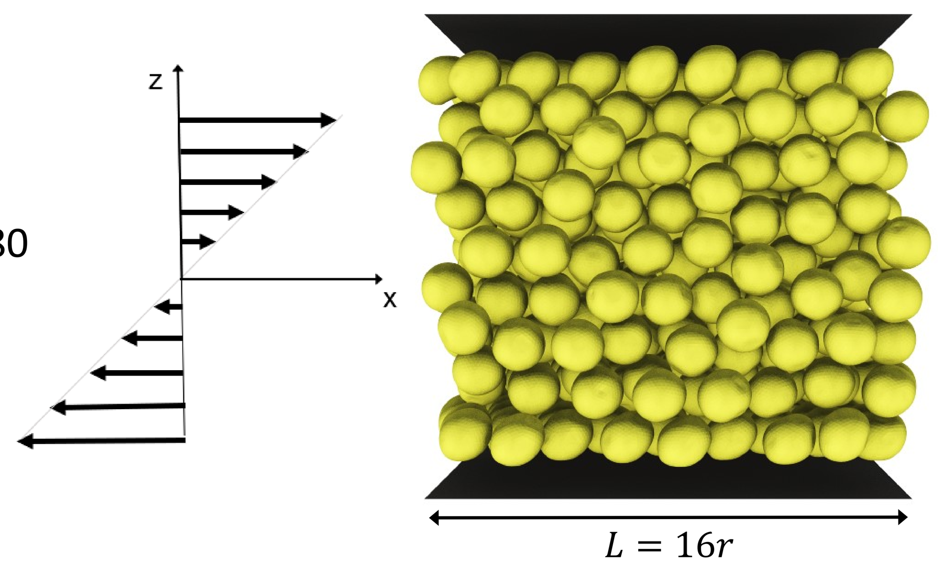

Figure 1: Schematic of the simulation setup depicting a suspension at $\phi = 0.5$.

Deformation of Skalak capsules in a shear flow

We start by fixing C and investigating the deformation of a suspension of capsules as function of both the volume fraction and capillary number.

- Taylor deformation index:

$$\langle D\rangle = \frac{\langle r_1\rangle - \langle r_3\rangle}{\langle r_1\rangle + \langle r_3\rangle}$$

- Capillary number:

$$C_a = \frac{\mu_0 r\dot{\gamma}}{G_s}$$

- Membrane inextensibility:

$$C = \frac{G_A}{G_s}$$

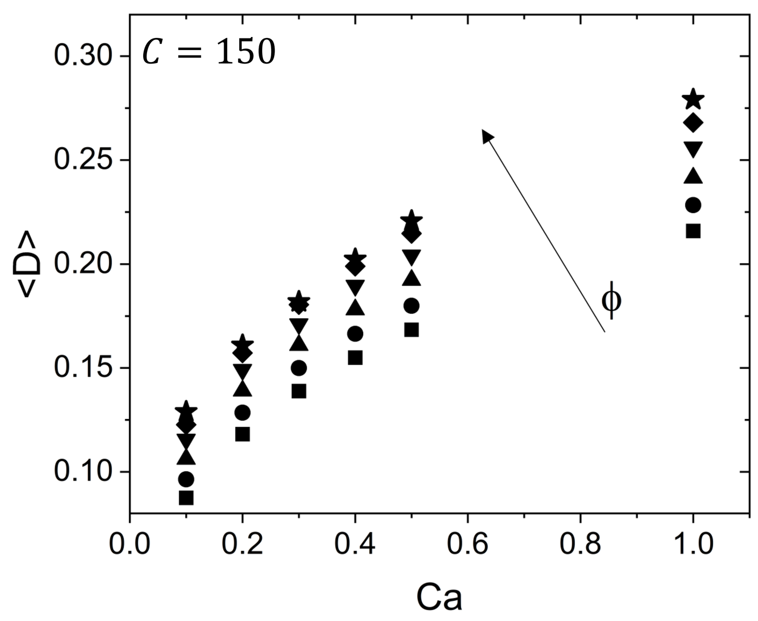

Figure 2: Deformation of a suspension of capsules as function of the shear rate.

➢ $\langle D\rangle$ increases linearly with ϕ for a fixed C_a.

For a better understanding of the interplay between C_a and C, we focus here on the deformation of a single capsule.

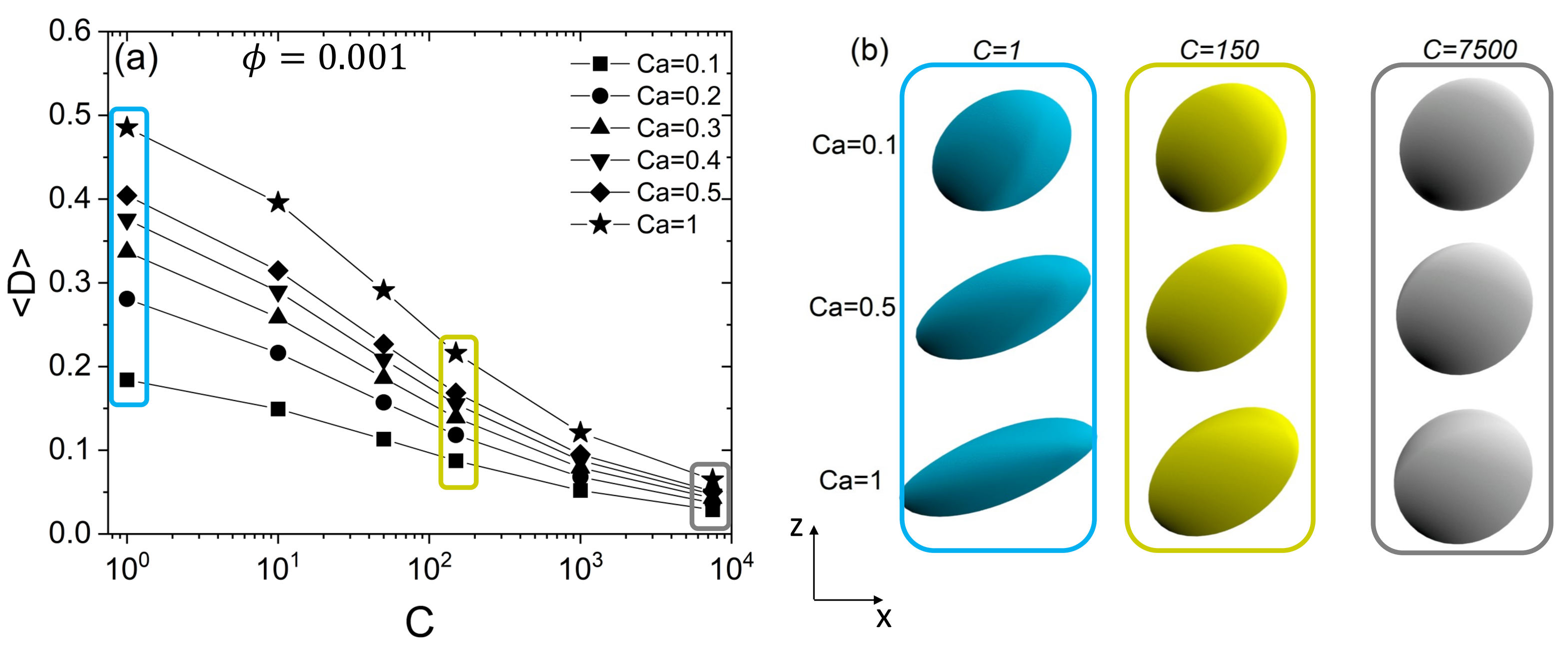

Figure 3: (a) Deformation of a single capsule as function of the C for different C_a. (b) Selected steady-state shape of the deformed capsule.

➢ $\langle D\rangle$ depends on both C and C_a, and the dependency on C_a gets weaker as C increases.

Based on the knowledge gained from the interplay between C, C_a, and ϕ on $\langle D\rangle$, we consider the following assumptions on the mean deformation of the particles:

- $\langle D\rangle$ shows linearity in ϕ.
- $\langle D\rangle$ is constant (with C_a) intrinsic viscosity $[\mu] \approx 2.8$ (equal to its large C limit).
- Extra-tension on the membrane surface accounting for non-zero C.

Our assumptions lead to:

$$\mu_0 \to \mu_{eff} = \mu_0(1+[\mu]\phi)$$
$$G_s \to G_s^{(eff)} = G_s(1+\alpha C)$$

We then introduce an effective capillary number reading as:

$$Ca_{eff}(\phi, C) = \frac{\mu_{eff}\dot{\gamma}r}{G_s^{(eff)}} \equiv \frac{(1+[\mu]\phi)}{(1+\alpha C)}Ca$$

When plotted as function of Ca_{eff}, the values of $\langle D\rangle$ for different ϕ and C collapse onto a ***single master curve***. Such curve can be fitted using:

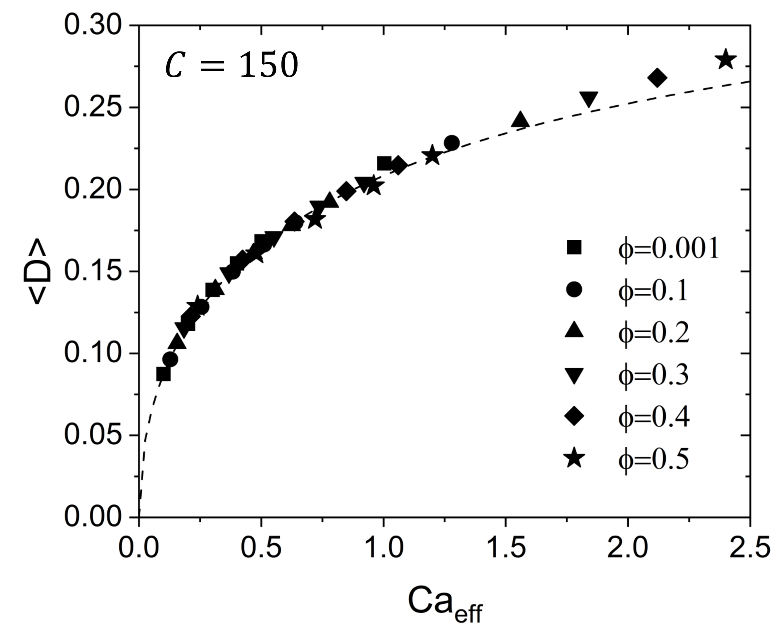

Figure 4: Deformation parameter as function of the effective capillary number.

$$\langle D\rangle \equiv \mathfrak{D}(C_a, \phi, C) = Ag\left(\frac{C_a}{C_a^*(\phi, C)}\right); \quad \text{with } C_a^* \propto \frac{G_s^{(eff)}(C)}{\mu_{eff}(\phi)} \text{ and } g(x) = x^{0.3}(1-e^{-x^{0.7}})$$

Suspension rheology in a shear flow

We scan the parameter space (C_a, C, ϕ) within the ranges $C_a \in [0.1, 1]$, $C \in [10^{-3}, 7.5\times10^{3}]$ and $\phi \in [10^{-3}, 0.5]$ to determine the rheological behaviour of the suspension by measuring the relative viscosity which is defined as:

$$\mu_r = 1 + \Sigma_{xz}^{p} / \mu_0\dot{\gamma}$$

Examples of steady-state configurations of the suspension are shown in Fig. 5.

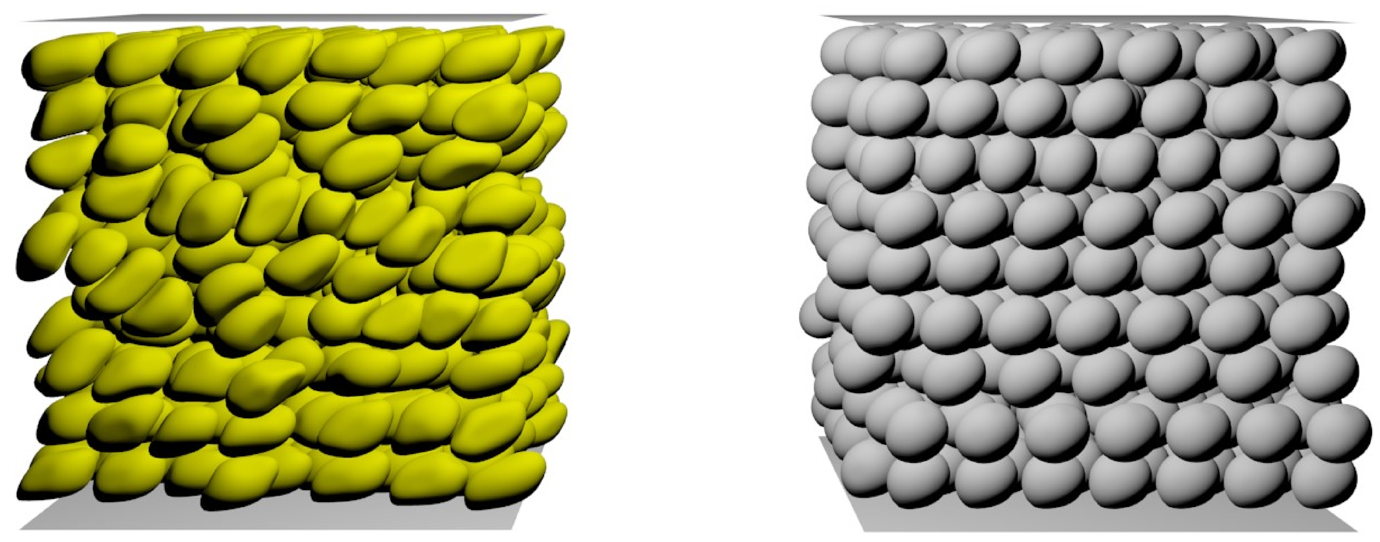

Figure 5: Stead-state configuration of a suspension of capsules for $\phi = 0.5, C_a = 1$. Left: $C = 150$. Right: $C = 7500$. The initial configuration for both simulations is depicted in Fig. 1.

Relative viscosity:

➢ The growth of μ_r is approximately linear for $\phi \lesssim 0.1$ and then become steeper

➢ *Shear-thinning behaviour*: μ_r tends to decrease with C_a

➢ Shear-thinning behaviour *enhanced* as ϕ increases

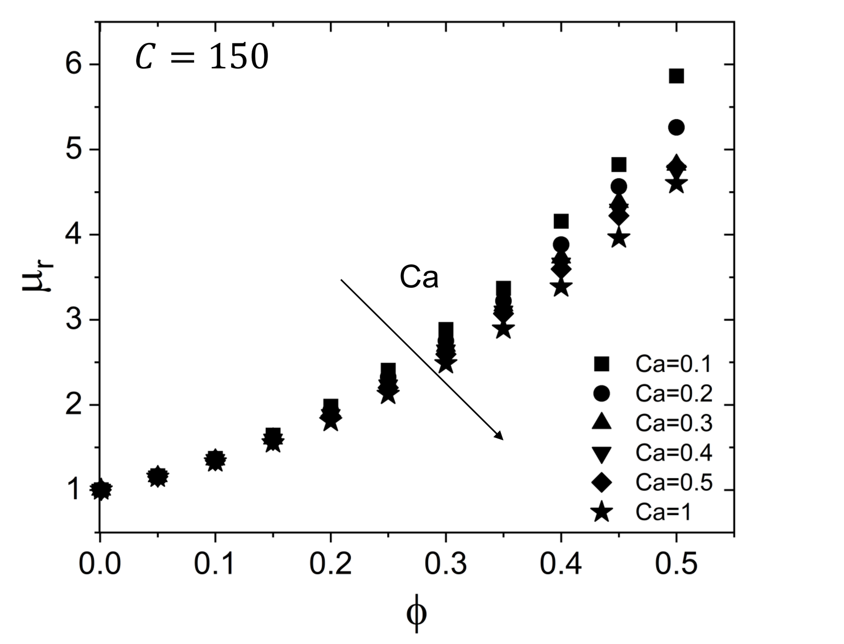

Figure 6: Relative viscosity as function the volume fraction.

Our **aim** is to find a ***universal behaviour*** of the **relative viscosity** across the various shears, as we did previously for the mean deformation of the particles.

Since ϕ is calculated based on the undeformed shape of the capsules, we start by introducing an effective volume fraction based on the results from the study of the mean deformation of the particles.

This effective volume fraction can be expressed as

$$\phi_{eff} = \frac{1-b\langle D\rangle}{1+b\langle D\rangle}\phi,$$

where b is a parameter related to the shape of the particles. For ellipsoidal particles, we find $b = 0.5$.

When plotting μ_r as function of ϕ_{eff}, we observe a nice overlap of all the data sets onto a ***single master curve*** that can be well fitted with an Eilers function reading as:

$$\mu_r = \left[1 + B\phi_{eff}/(1-(\phi_{eff}/\phi_m))\right]^2$$

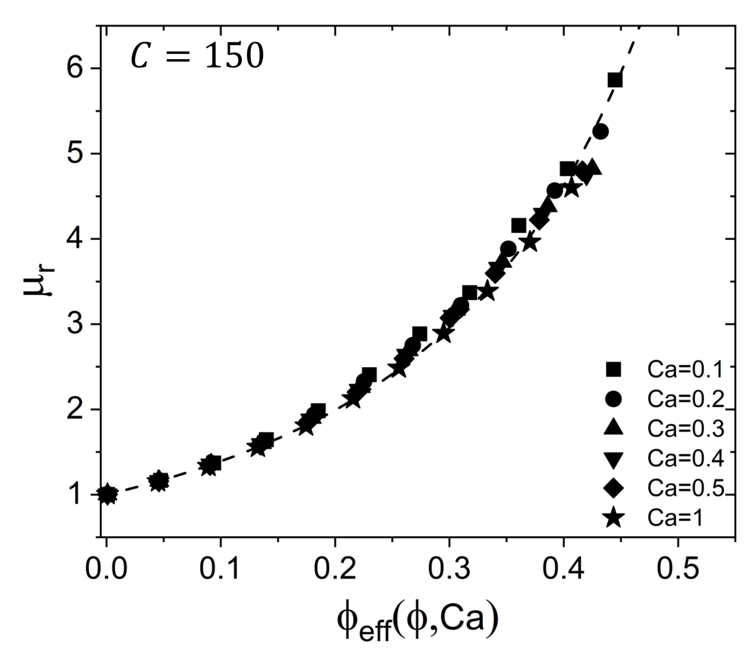

Figure 7: Relative viscosity as function of the effective volume fraction.