

MÉLANGE DANS LES SUSPENSIONS CISAILLÉES

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France

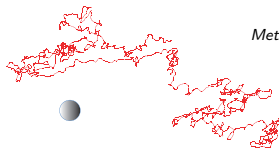
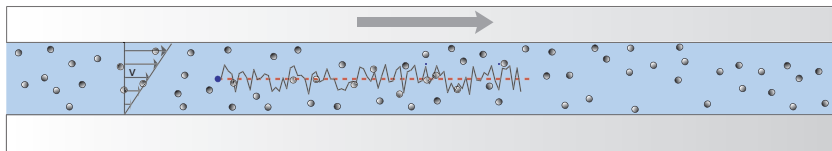
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Novembre 2015

MÉLANGE DANS LES SUSPENSIONS CISAILLÉES

- $\rho_{\text{fluide}} = \rho_{\text{particules}}$
- $Re \ll 1 \rightarrow$ fluide très visqueux
- $Pe_p \gg 1 \rightarrow$ particules non-browniennes



Metzger et al., JFM, 2013

← Diffusion induite par cisaillement

Problématique :

Comment quantifier le mélange induit par l'agitation des particules ?

① MÉLANGE EN CISAILLEMENT OSCILLANT

② MÉLANGE EN CISAILLEMENT CONTINU

DIFFUSION INDUITE PAR CISAILLEMENT ET MÉLANGE

- Eckstein *et al.* (1977) → Diffusion induite par cisaillement
- Wang et Koch (2009) → Transfert de masse (Méthode électrochimique)
- Metzger *et al.* (2013) → Transfert de chaleur dans une suspension cisailée
- Souzy *et al.* (2015) → Mécanisme de transfert de masse en proche paroi

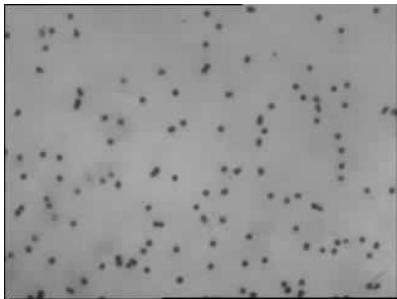
L'expérience de Taylor : Appliquer un cisaillement oscillant



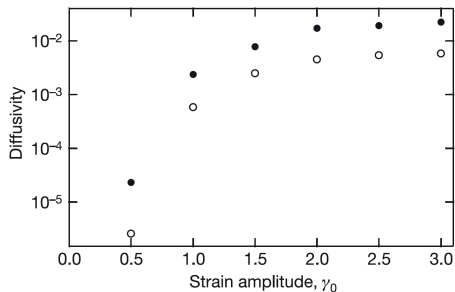
G.I. Taylor (1966)

→ Illustrer la réversibilité des écoulements à bas Re

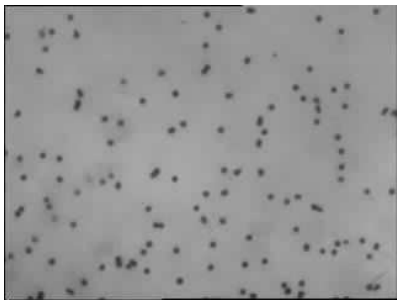
SUSPENSION DE PARTICULES EN CISAILLEMENT OSCILLANT



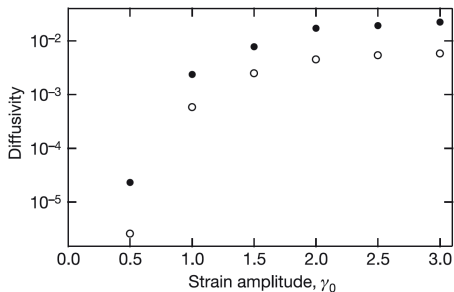
Film stroboscopique,
Pine et Gollub, Nature, 2005



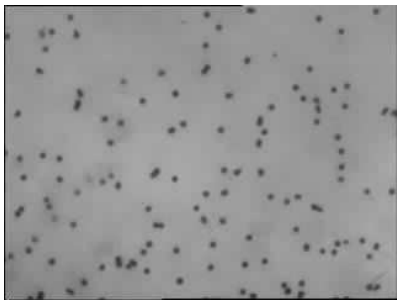
SUSPENSION DE PARTICULES EN CISAILLEMENT OSCILLANT



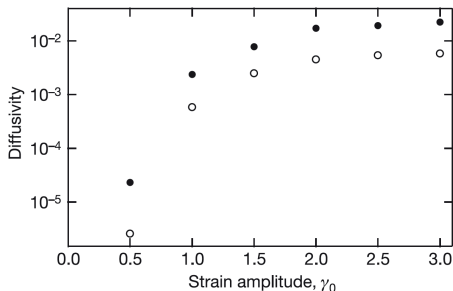
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SUSPENSION DE PARTICULES EN CISAILLEMENT OSCILLANT

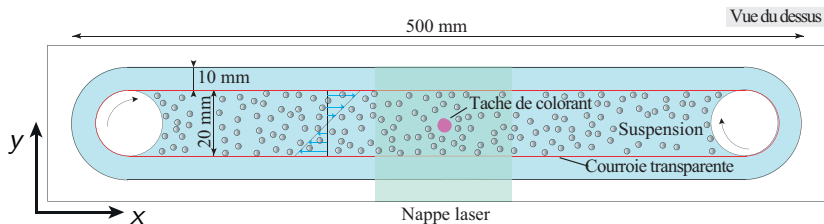


Film stroboscopique,
Pine et Gollub, Nature, 2005



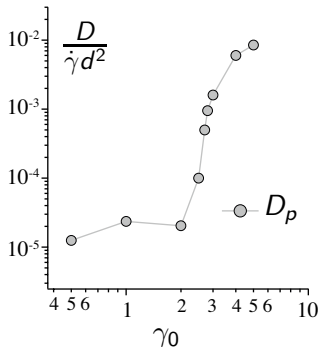
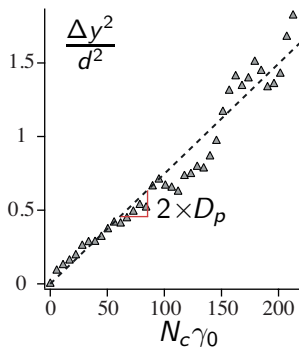
Que se passe-t-il lorsque l'on place une goutte de colorant dans la suspension ?

DISPOSITIF EXPERIMENTAL - CELLULE DE COUETTE PLAN-PLAN

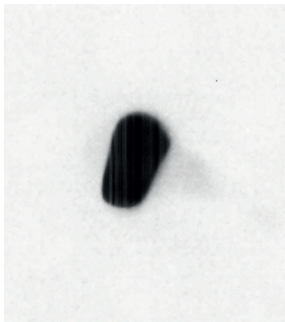


- Solution : Triton X-100, $ZnCl_2$, H_2O
- $d=2mm$
- $\phi=35\%$
- γ_0 : Amplitude cyclique de déformation
- $Pe_p \gg 1$
- $Re \ll 1$
- $\rho_{fluide} = \rho_{particules}$
- N_C : Nombre de cycles

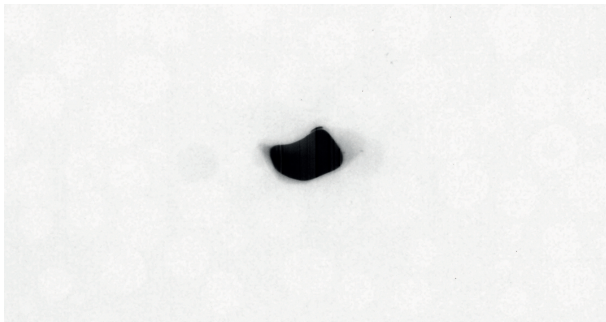
"PARTICLE TRACKING"



DÉFORMATION D'UNE GOUTTE DE COLORANT



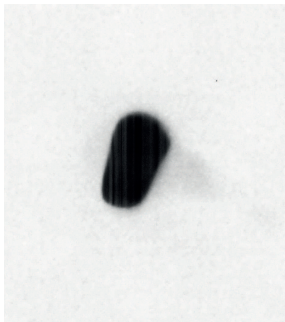
$$\gamma_0 = 0.5$$



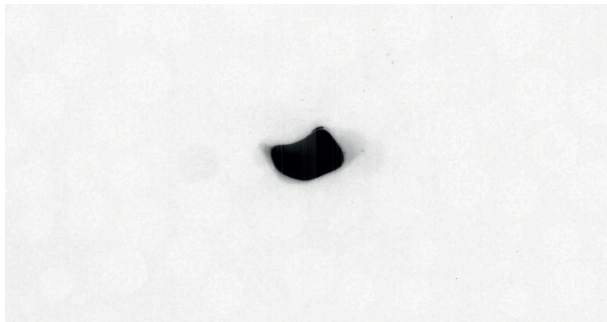
$$\gamma_0 = 4$$

- $D_0 \approx 10^{-13} \text{m}^2 \cdot \text{s}^{-1}$

DÉFORMATION D'UNE GOUTTE DE COLORANT



$$\gamma_0 = 0.5$$

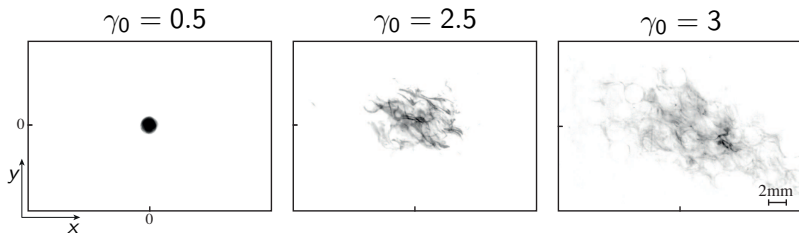


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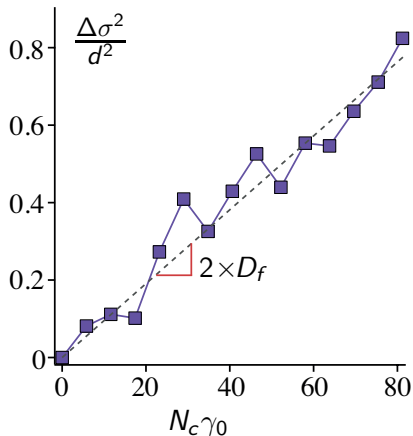
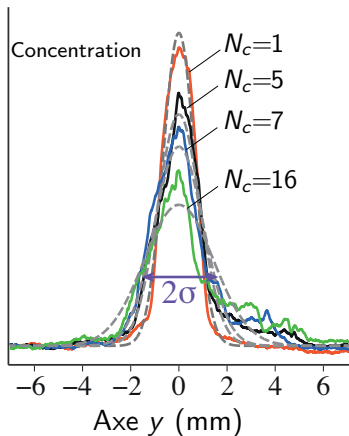
- $D_0 \approx 10^{-13} \text{m}^2 \cdot \text{s}^{-1}$

DÉFORMATION D'UNE GOUTTE DE COLORANT

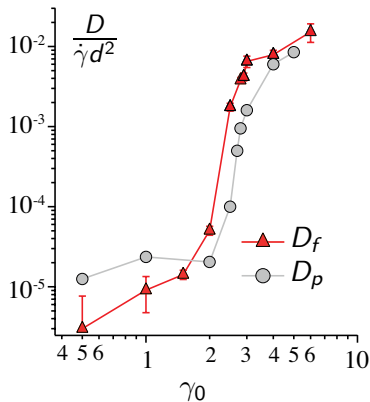
Après $N_c = 40$ cycles :



DISPERSION DES NIVEAUX DE CONCENTRATION



COEFFICIENTS DE DIFFUSION

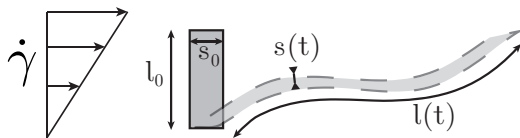


Pour $\gamma_0 > \gamma_c \rightarrow \frac{D_f}{D_0} \approx 10^4$

1 MÉLANGE EN CISAILLEMENT OSCILLANT

2 MÉLANGE EN CISAILLEMENT CONTINU

CHARACTÉRISATION DU MÉLANGE : LOIS D'ÉTIREMENT



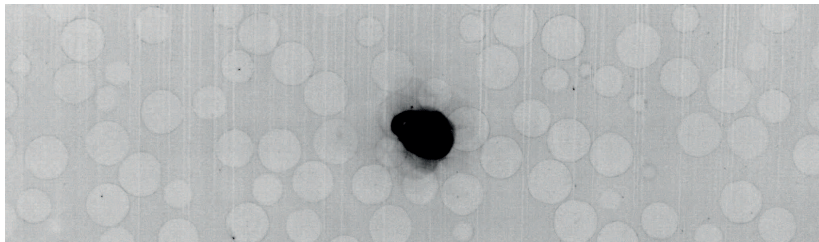
$$\rho = \frac{l(t)}{l_0} = ?$$

CARACTÉRISATION DU MÉLANGE : LOIS D'ÉTIREMENT

Fluide pur :



Suspension :

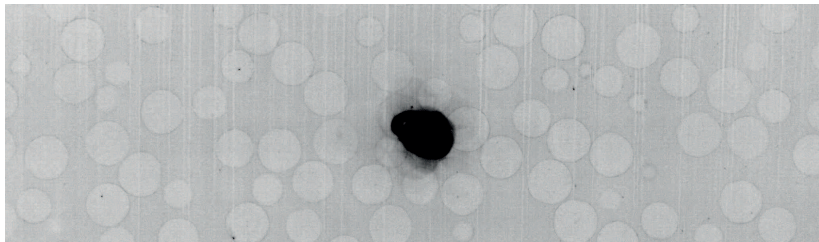


CARACTÉRISATION DU MÉLANGE : LOIS D'ÉTIREMENT

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Suspension :

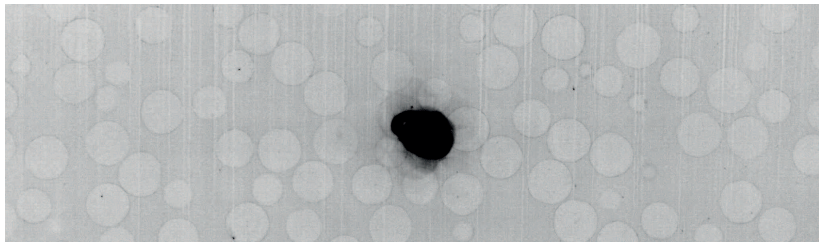


CARACTÉRISATION DU MÉLANGE : LOIS D'ÉTIREMENT

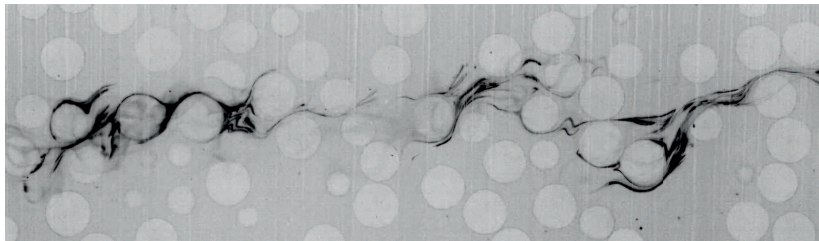
Fluide pur :



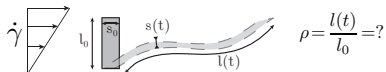
Suspension :



MÉLANGE : UNE APPROCHE EN 2 ÉTAPES

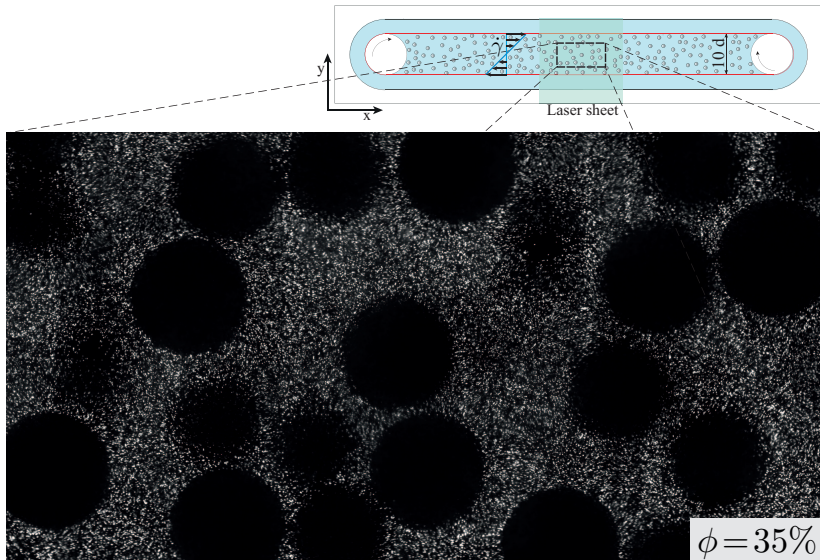


i) Caractériser l'advection

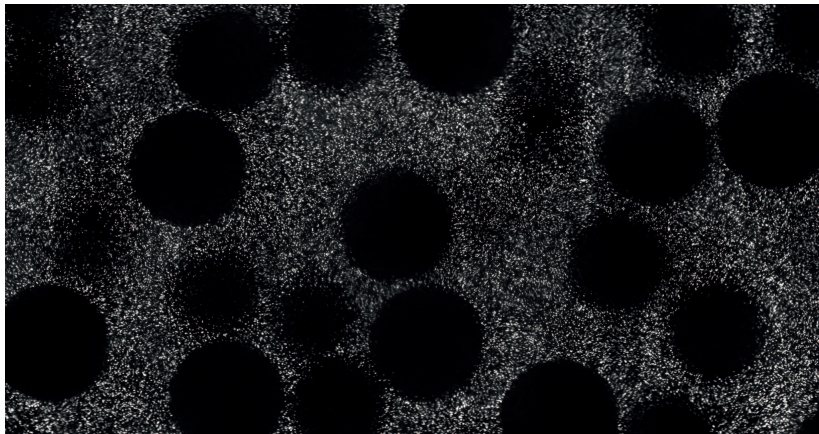
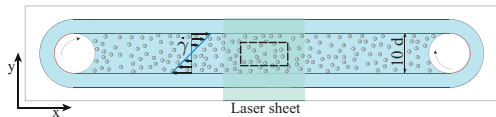


ii) Brancher la diffusion moléculaire \rightarrow Prédications de PDF(C)

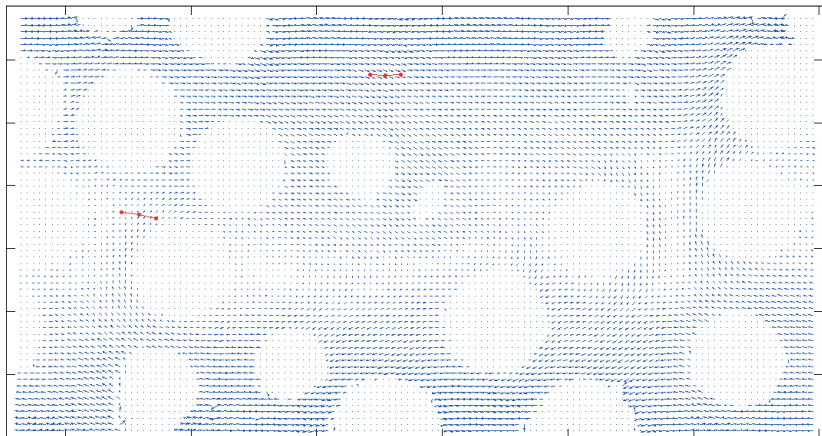
PIV DANS LA PHASE FLUIDE



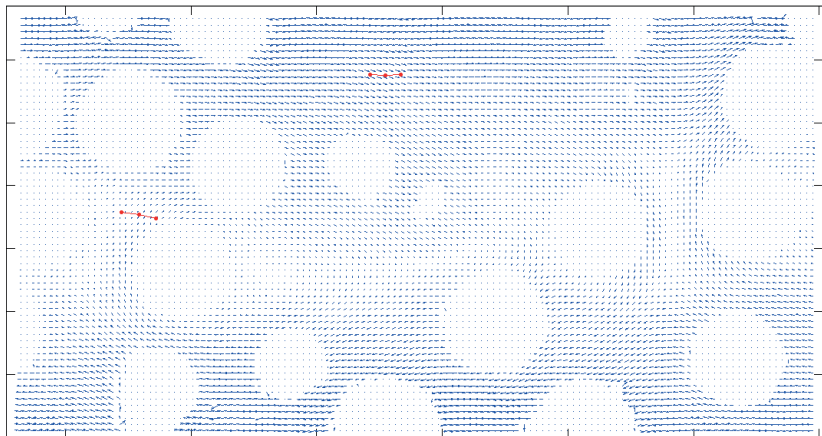
PIV DANS LA PHASE FLUIDE

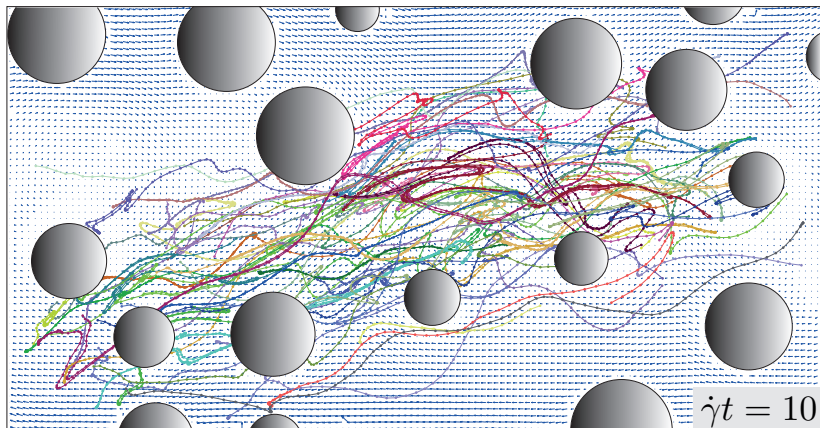


ADVECTION NUMÉRIQUE DANS L'ÉCOULEMENT MESURÉ



ADVECTION NUMÉRIQUE DANS L'ÉCOULEMENT MESURÉ

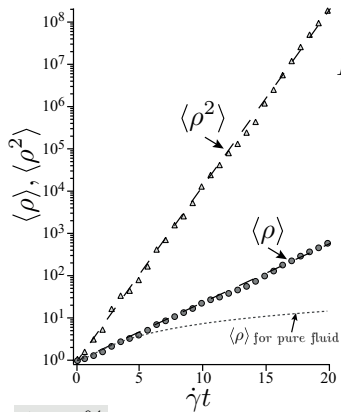




- Nombre de segments ≈ 25000

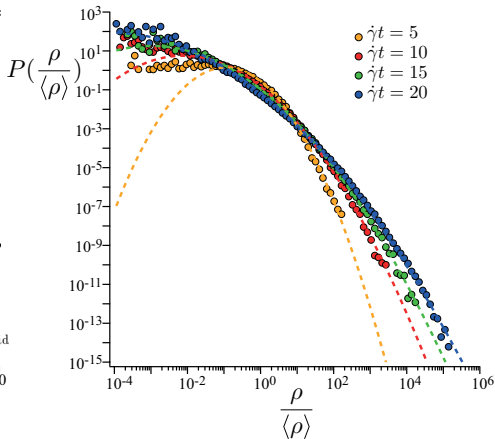
- $\rho = \frac{l(t)}{l_0} = ?$

LOIS D'ÉTIREMENT



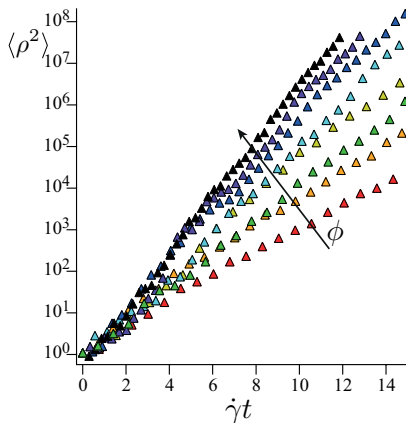
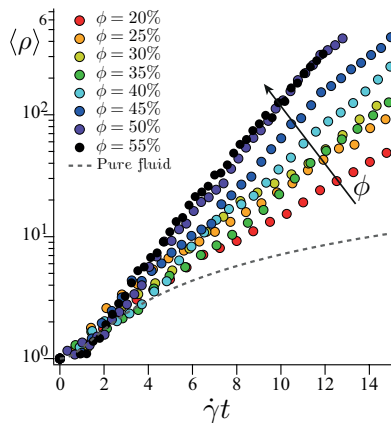
$\phi = 35\%$

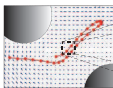
- Etirement exponentiel



- Distribution log-normale

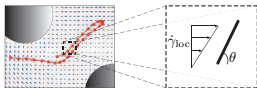
LOIS D'ÉTIREMENT



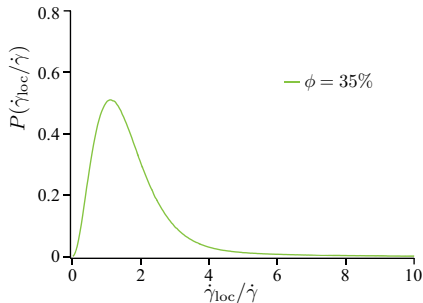
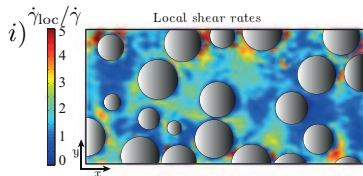


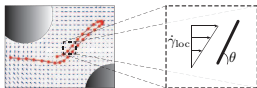
Locally: simple shear
Average over θ

$$\left. \begin{array}{l} \text{Locally: simple shear} \\ \text{Average over } \theta \end{array} \right\} \rho^2(t) = 1 + \frac{(\dot{\gamma}_{\text{loc}} t)^2}{2}$$

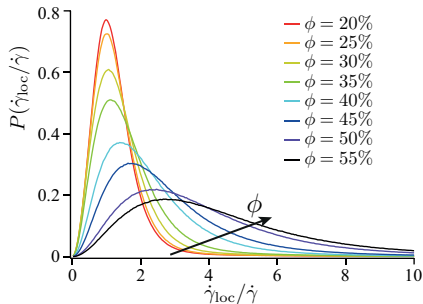
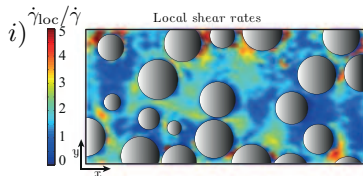


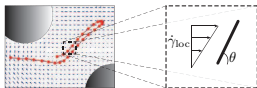
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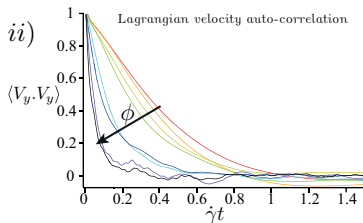
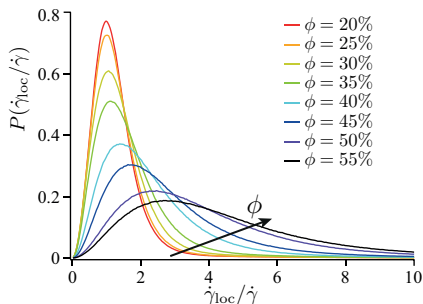
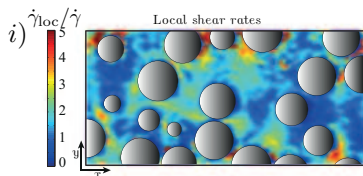


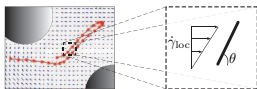
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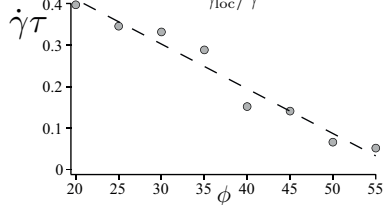
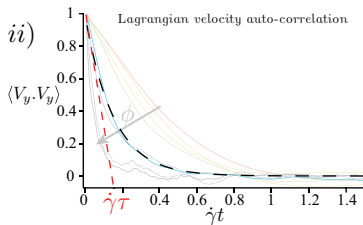
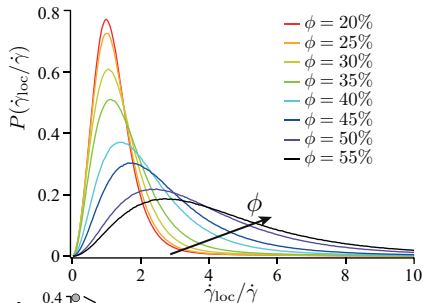
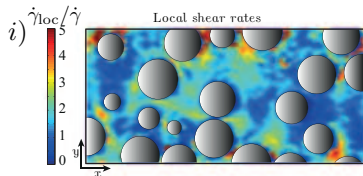
Locally: simple shear } $\rho^2(t) = 1 + \frac{(\dot{\gamma}_{loc}t)^2}{2}$
 Average over θ





Locally: simple shear
Average over θ

$$\rho^2(t) = 1 + \frac{(\dot{\gamma}_{loc} t)^2}{2}$$



MODÈLE - PROCESSUS D'ÉTIREMENT MULTIPLICATIF

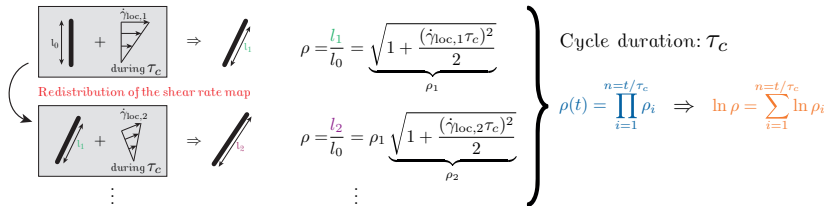


Redistribution of the shear rate map

$$\rho = \frac{l_1}{l_0} = \sqrt{1 + \frac{(\dot{\gamma}_{loc,1}\tau_c)^2}{2}}$$

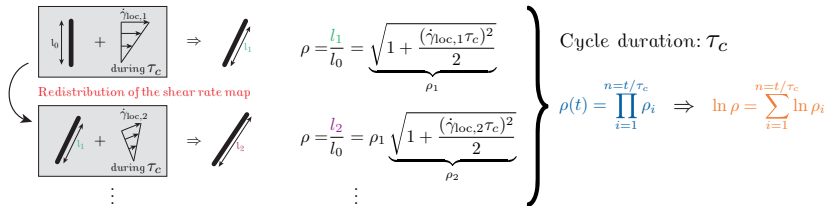
Cycle duration: τ_c

MODÈLE - PROCESSUS D'ÉTIREMENT MULTIPLICATIF



$\ln \rho$: Distribution normale \implies ρ : Distribution log-normale

MODÈLE - PROCESSUS D'ÉTIREMENT MULTIPLICATIF



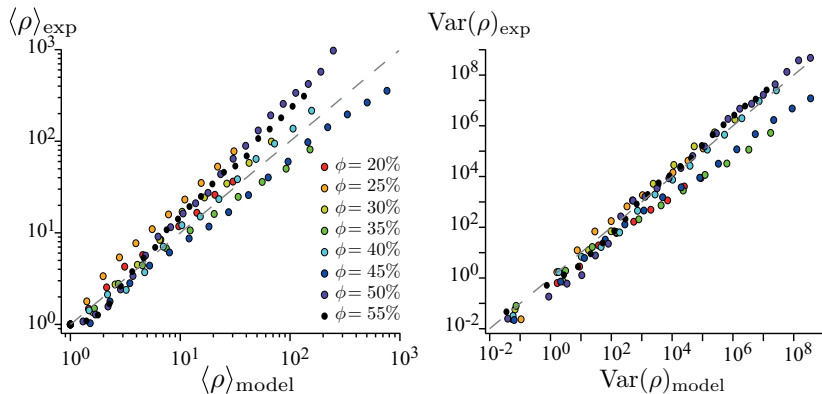
$\ln \rho$: Distribution normale $\Rightarrow \rho$: Distribution log-normale

$$\langle \ln \rho \rangle = \frac{t}{2\alpha\tau} \left\langle \ln \left(1 + \frac{(\dot{\gamma}_{loc}\alpha\tau)^2}{2} \right) \right\rangle$$

$$Var(\ln \rho) = \frac{t}{4\beta\tau} \left[\left\langle \ln^2 \left(1 + \frac{(\dot{\gamma}_{loc}\beta\tau)^2}{2} \right) \right\rangle - \left\langle \ln \left(1 + \frac{(\dot{\gamma}_{loc}\alpha\tau)^2}{2} \right) \right\rangle^2 \right]$$

α, β : Paramètres de structure d'ordre 1

COMPARAISON AVEC LE MODÈLE



$$\alpha = 0.3$$

$$\beta = 5.2$$

⇐ Même valeur pour tous les ϕ

i) Caractériser l'advection $\Rightarrow PDF(\rho(\phi))$

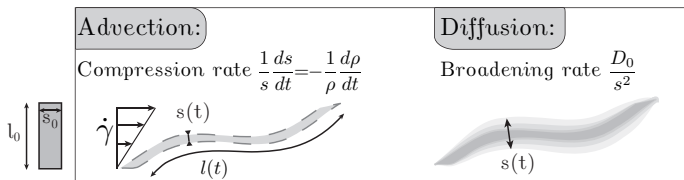


MÉLANGE : UNE APPROCHE EN 2 ÉTAPES

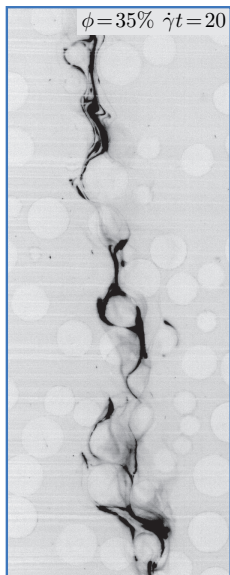
i) Caractériser l'advection \Rightarrow PDF($\rho(\phi)$)



ii) Brancher la diffusion moléculaire

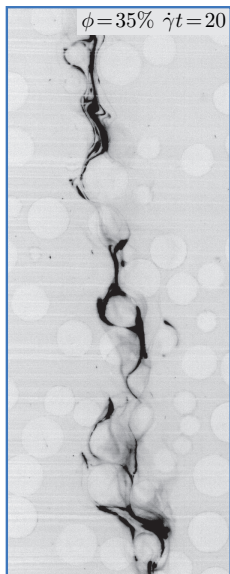


$$\text{For } t = t_{\text{mix}} \quad \frac{1}{s} \frac{ds}{dt} = \frac{D_0}{s^2} \quad \Rightarrow \quad \begin{cases} l(t) = l_0 e^{\omega t} \rightarrow s(t) = s_0 e^{-\omega t} \\ t_{\text{mix}} = \frac{1}{2\omega} \ln\left(1 + \frac{2\omega s_0^2}{D_0}\right) \\ \omega \sim \frac{\langle \dot{\gamma}_{\text{loc}}(\phi)^2 \rangle \alpha \tau(\phi)}{2} \end{cases}$$



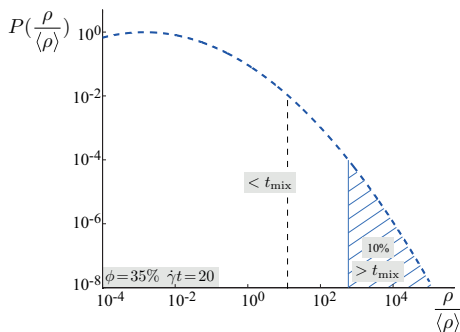
$$t_{\text{mix}}(\phi) = \frac{1}{\langle \dot{\gamma}_{\text{loc}}(\phi)^2 \rangle \alpha \tau(\phi)} \ln \left(1 + \frac{\langle \dot{\gamma}_{\text{loc}}(\phi)^2 \rangle \alpha \tau(\phi) s_0^2}{D_0} \right)$$

\Rightarrow For $\phi = 35\%$: $\dot{\gamma}t_{\text{mix}} \approx 50$



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\Rightarrow For $\phi = 35\%$: $\dot{\gamma}t_{\text{mix}} \approx 50$



\Rightarrow Prédiction des PDF(C)...