Continuum mechanics description of foam flows

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Eur Phys J E 2011, J Rheol in press 2012

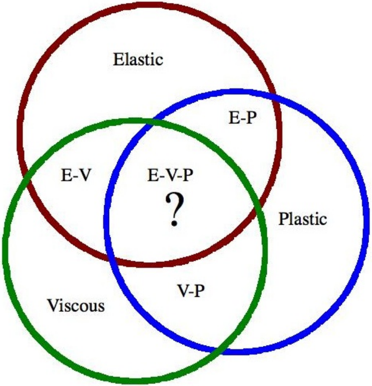
Scales

- individual : bubble
- “mesoscopic" : group of bubbles
- global : foam flow

What can we ask from models ?

- from individual to mesoscopic :
  determine material parameters - viscosity, shear modulus
- from mesoscopic to global :
  use these parameters to predict the flow

Complete continuous models ?



Existing continuous models :
Janiaud et al. PRL 2006 : 1D, friction of plates
Katgert et al. PRL 2008 : 1D, friction of plates, non-linearities
Goyon - Bocquet - Colin 2009-2010 : 1D, long range effect of T1s
Marmottant et al. EPJE 2007 : 3D, progressive plasticity
Benito et al. EPJE 2008, 2012 : 3D, non-linear elasticity
Saramito JNNFM 2007, 2009 : 3D, obeys the second principle

Requirements

Optimum between simplicity and completeness :

- Find which rheology is required to capture the physics
- Answer the engineer's questions
- Model parameters measurable in experiments and simulations

Model ingredients

Main ingredients :

- viscous, elastic, plastic
- tensorial

Two material parameters :

- yield strain ε_Y
- a characteristic time, adimensioned ; eg :
  visco-plastic : Bingham $= \frac{\tau_Y L}{\eta V}$
  visco-elastic : Weissenberg $= \frac{\eta V}{GL} = \frac{2\varepsilon_Y}{Bi}$

Various flows

Flows in a geometry without stress heterogeneity :

- simple shear
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Flows in a geometry with stress heterogeneity, 2D or 3D :

- Couette : between // or concentric plates $\longrightarrow$ predict localisation length ?
- Stokes : around an obstacle $\longrightarrow$ predict velocity field ?
- Poiseuille : in a channel
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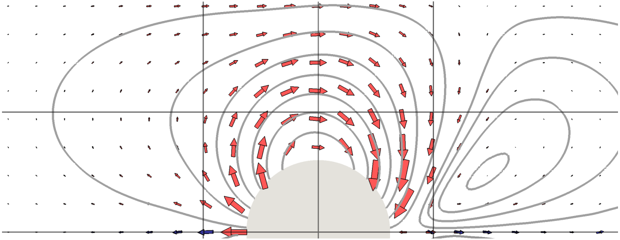
Cheddadi 2011, 2012 + in progress

Predict Stokes ?

Main parameter : yield strain

map of velocity field - calculated in the half-plane



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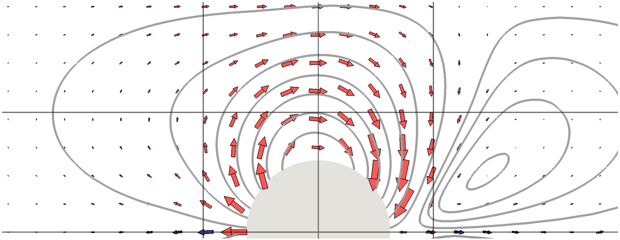
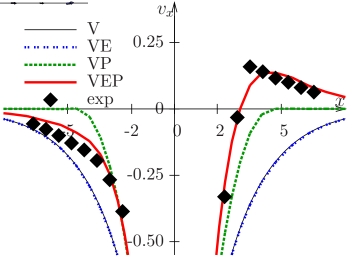


Real visico-elasto-plastic

- up- / down-stream asymmetry
- overshoot in velocity
- zero-velocity point behind the obstacle

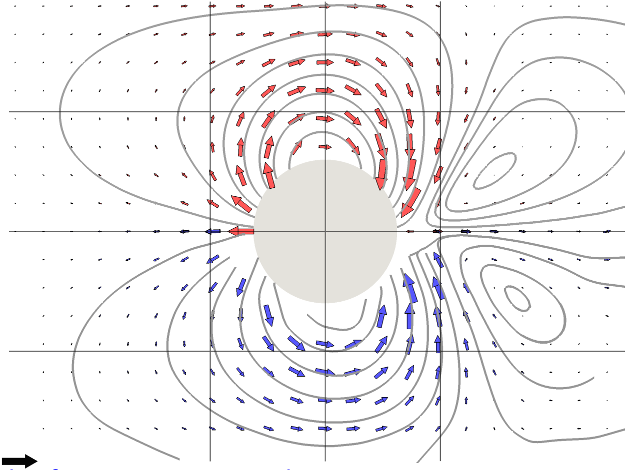
speed along the main axis $y = 0$
referential moving with the foam



Test of prediction : $\mathbf{v} - \boldsymbol{V}_{in}$

Cheddadi et al, Eur. Phys. J. E (2011)

prediction : continuous model



dry foam experiment : discrete measurements

Good agreement

- amplitude of $\mathbf{v}$
- orientation of $\mathbf{v}$
- recirculation zones
- arrest points
- overshoot

Test of prediction : strain

Cheddadi et al, Eur. Phys. J. E (2011)

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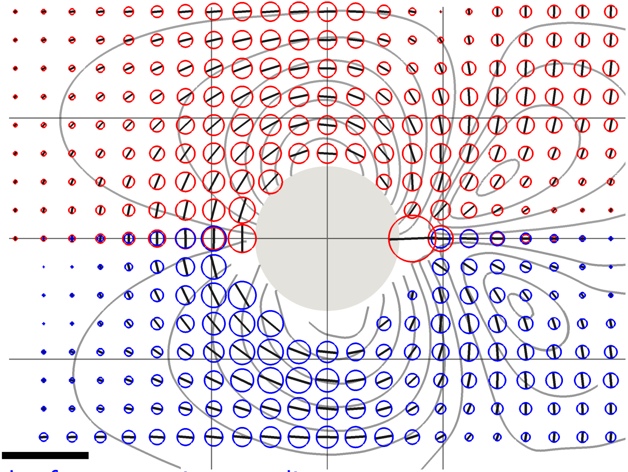


dry foam experiment : discrete measurements

Systematic tests
of all quantities

Conclusions

Continuous model at global scale = useful for physicist, mechanician, engineer ?

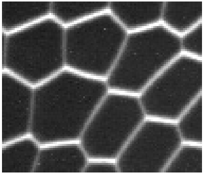
- seems predictive
- contributes to debates :
  origin of localisation, discontinuity, non-uniqueness, overshoot
- stress versus total deformation rate & elastic deformation
  $\rightarrow$ visco-plastic Herschel-Bulkley in steady one-dimensional flow
- visco-elasto-plastic tensorial required to capture physics ;
  non trivial effects
- parameter with the strongest effect : yield strain
- covers a realistic range of velocities
  4 decades, limited by coarsening and film breakage

Even more open questions, including :

- more details about bubble shape : Gay & Cantat
- non-locality : Bocquet & Goyon
- quasistatic ($v \rightarrow 0$ not equivalent to $v = 0$) : Marmottant
- statistical effects : fluctuations, correlations, jamming, avalanches
- high speed : carbopol experiments

Viscous, elastic, plastic (VEP) behaviour

Marmottant 2007



local energy minimum

Small deformation

elastic solid

reversibly comes back
to its initial shape

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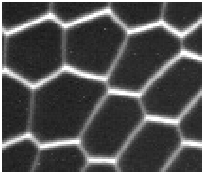

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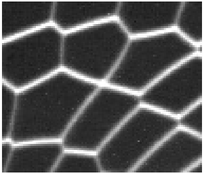

T1 : neighbour change

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Large deformation

plastic solid

irreversibly sculpted, new shape

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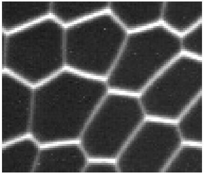

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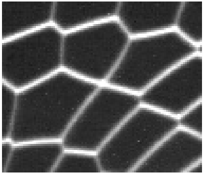

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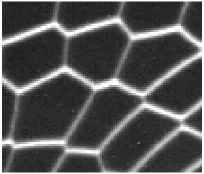

relaxation → other minimum

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Quick deformation rate

viscous liquid

irreversibly flows, stress increases with rate

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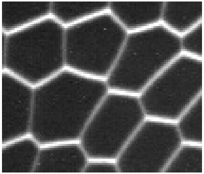

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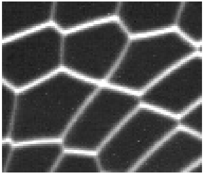

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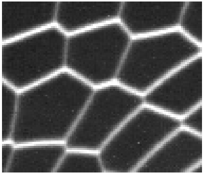

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Advantages of foams — especially in 2 dimensions

- Disordered units which rearrange — model for : droplets, polymers, atoms, cells
- Bubbles act as tracers — velocity, deformation, plastic events
- Multi-scale visualisation — micro-structure & global flow

Discriminant experiment

Dollet, Graner, JFM 07

- controlled, reproducible flow
- variety of shears and elastic deformations
- **two or more dimensions** of space

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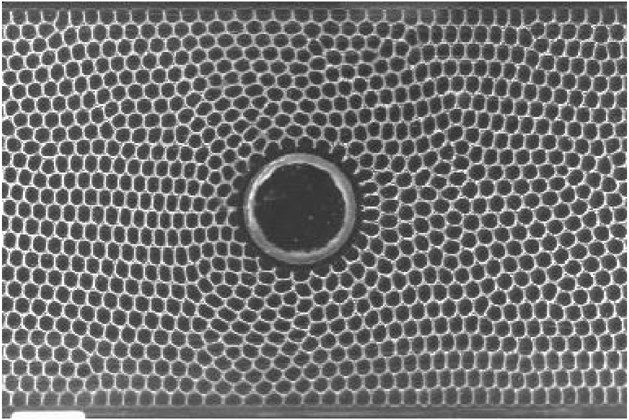


B. Dollet

wet foam, $\phi = 7\%$

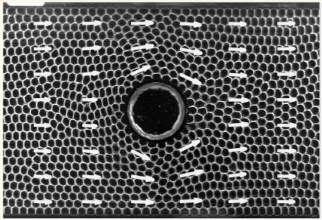
flow around an obstacle

$V = 1$ cm/s

Statistical measurements

Graner et al. 2008, Marmottant et al. 2008

Velocity



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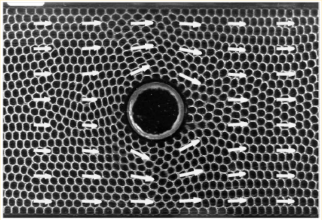
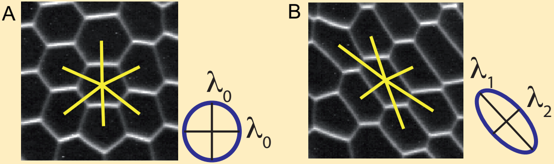


Texture

Bubble shape and packing



isotropic
circle

anisotropic
ellipse

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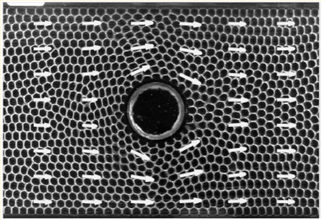

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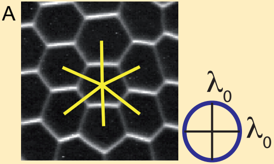

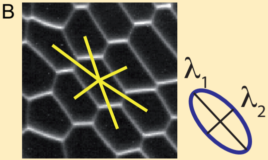

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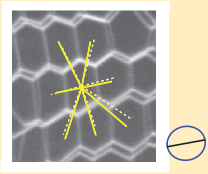
Velocity gradient

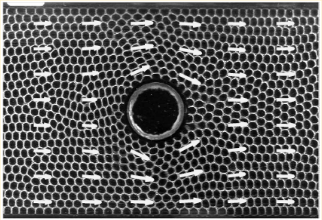


Shape change

Statistical measurements

Graner et al. 2008, Marmottant et al. 2008

Velocity



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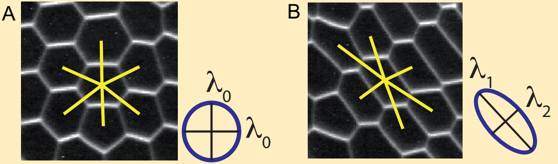

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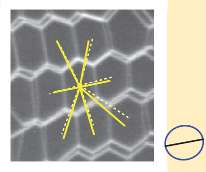
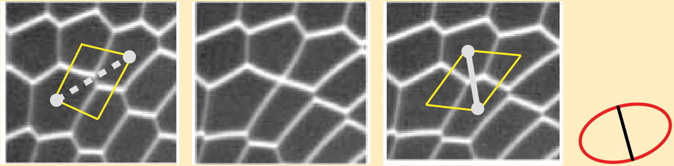


Shape change

Plasticity

Neighbour swapping : T1



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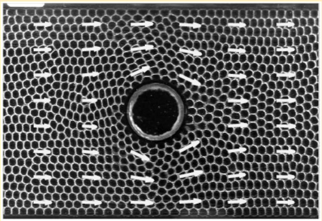

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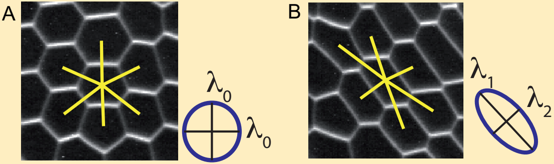

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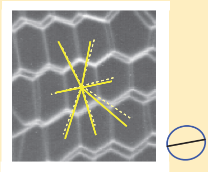

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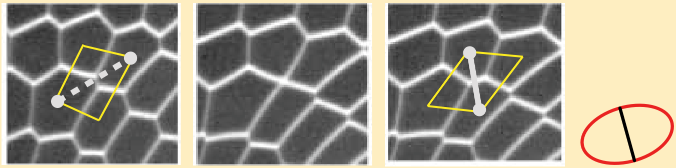

V, E and P contributions are expressed in the same units