Diffuse Interface Models for Metal Foams

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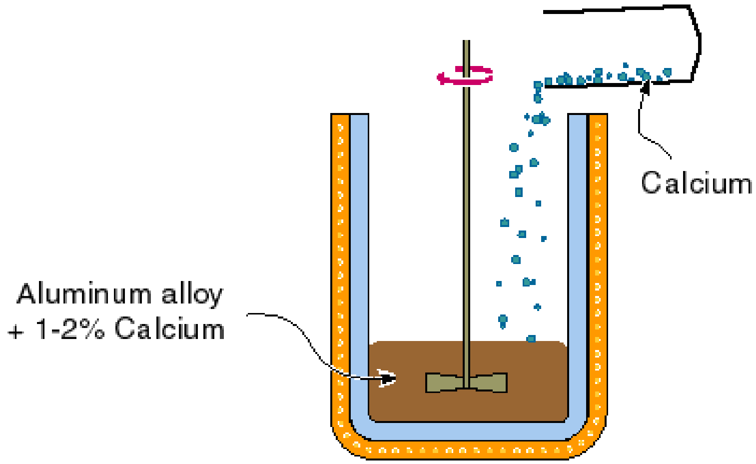
COMSOL CONFERENCE ROTTERDAM 2013

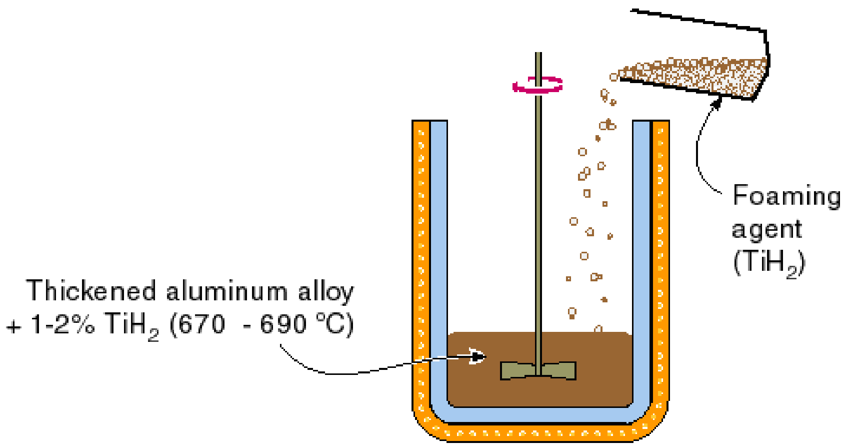
October 23-25

Presentation overview

- Introduction
- Metal foams with foaming agents in the melt
- Physical model
- Governing equations
- Simulations by Comsol Multiphysics
- Results
- Conclusions

Decomposition of foaming agents in the melt

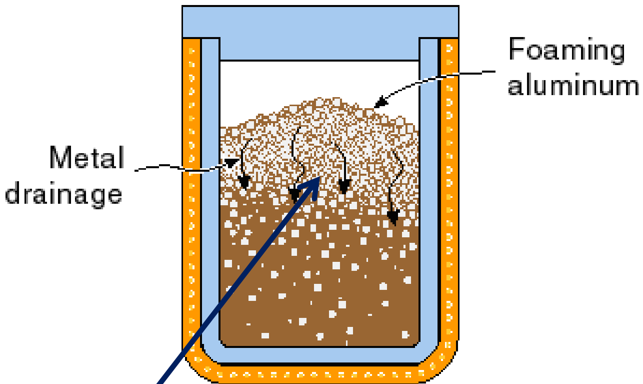




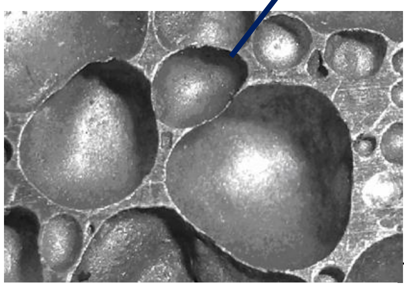
Foaming process (ALPORAS) for aluminium:

- base metal melting
- temperature stabilization
- viscosity raising adding 1-2% Ca
- aggressive stirring
- adding of foaming agent powder
- short stirring
- withdrawing of the stirring system

Decomposition of foaming agents in the melt

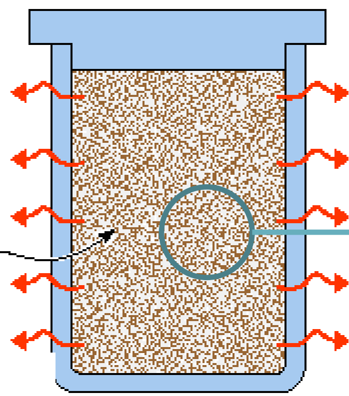


- - crucible sealing
- - foam formation controlled by adjusting overpressure, temperature and time
- - cooling of foamed aluminium
- - withdrawing.

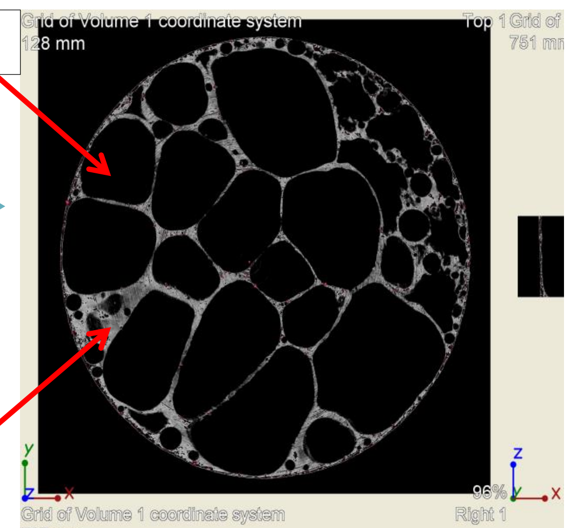


Al metal foam:

melted Al and H_2 gas



H_2 bubble



Al (or Al alloy)

Decomposition of foaming agents in the melt: physical phenomena

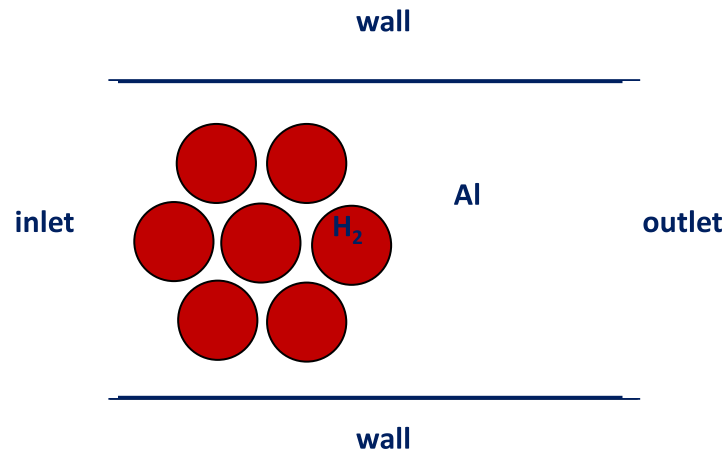
Foaming is a complex phenomena:

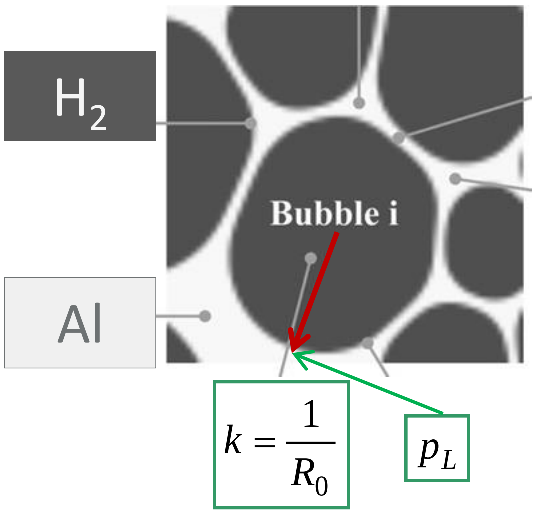
- simultaneous mass, momentum and energy transfer mechanisms
- several physical phenomena on interfaces: surface tension effects, disjoining pressure, interface motion
- **bubble dynamics, coarsening, coalescence, rupture**
- other aspects (drainage, mould filling, geometry)
- difficulty for experimental measurements (foams are hot, opaque, etc.)

Physical model

- A 2D rectangular cavity where melted Al and H_2 gas bubbles are flowing inside during the foaming process.
- Isothermal process, mass diffusion is not considered and gravity is absent (cavity is set horizontally).
- The gas follows the ideal gas law, the liquid is considered an incompressible Newtonian fluid, the two fluids are immiscible.
- The bubbles have the same radius and pressure, the gas-liquid interface is a free surface with uniform surface tension coefficient.
- With system at rest, the stress balance at the surface of a circular bubble is given by the Laplace's equation (capillary pressure):

$$p_{G,0} = p_L + \sigma k$$





Physical model

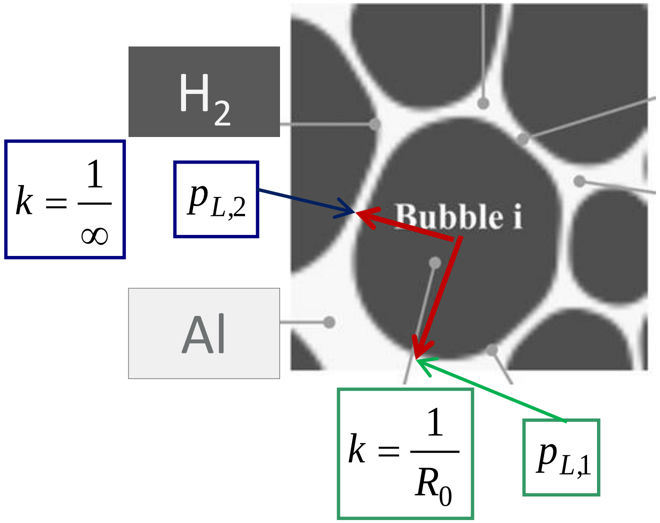
The liquid metal is suctioned from the capillary films to the borders of the foam (Plateau borders) causing the interfaces to thin and bubbles **to merge.**

The drainage of the thin films is slowed and prevented when interactions between the film surfaces come into play: these effects are represented by a pressure, the ***disjoining pressure*** $\Pi(h)$ (attractive and repulsive molecular forces in the thin film).

In the model, once ***the film h between the bubbles became sufficiently small***, we take into account the disjoining pressure $\Pi(h)$ (representing a stabilization effect suppressing the driving force for film thinning):

$$p_{G,0} = p_L + \sigma k$$

$$\boxed{p_{G,0} \text{ is the same } \Rightarrow p_{L,2} > p_{L,1}}$$



$$p_{G,0} = p_L + \sigma k + \Pi(h) \longleftarrow \boxed{\text{disjoining pressure}}$$

Simulations by Comsol Multiphysics 4.3b

Equations (coupled) (CDF and Chemical Reaction Engineering modules):

continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

momentum transfer

1. **gas compressibility neglected**
2. **flow is laminar**

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + \mathbf{F}_{st} + \mathbf{F}_{ext} + \mathbf{F}$$

interface movement (phase field ϕ)

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \nabla \cdot \frac{\gamma \lambda}{\varepsilon^2} \nabla \psi$$

$$\psi = -\nabla \cdot \varepsilon^2 \nabla \phi + (\phi^2 - 1)\phi + \left(\frac{\varepsilon^2}{\lambda}\right) \frac{\partial f_{\text{ext}}}{\partial \phi}$$

help variable ψ

$$\mathbf{F}_{\text{st}} = \left(G - \frac{\partial f}{\partial \phi}\right) \nabla \phi$$

Surface tension force

in Comsol:

$$\mathbf{F}_{\text{ext}} = \left(\frac{\partial f}{\partial \phi}\right) \nabla \phi$$

$\phi = +1$ **hydrogen phase**

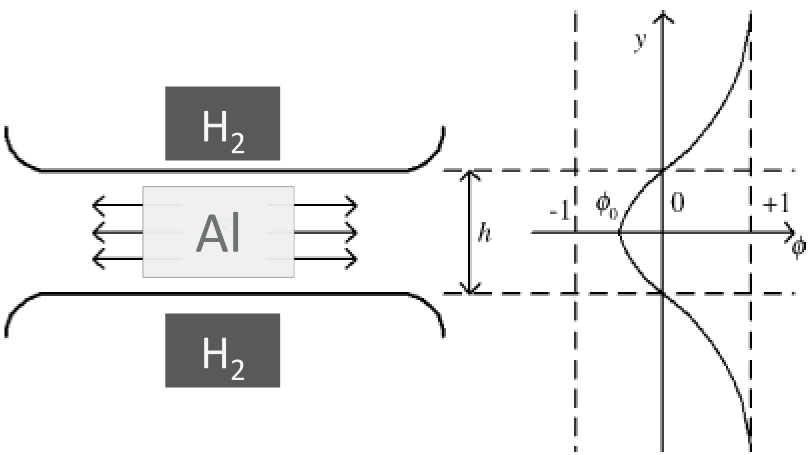
$\phi = -1$ **aluminium phase**

$\phi_{\text{int}} = 0$ **the middle of the interface**

But when two bubbles are approaching:

$$\Rightarrow \quad -1 < \phi_{\text{int}} = \phi_0 < 0$$

External force (due to the disjoining pressure)



Simulations by Comsol Multiphysics 4.3b

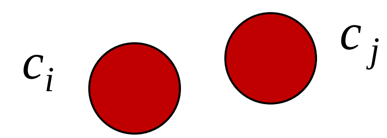
Yue *et al*. 2005:

$$\Pi(\phi) = -\frac{\lambda}{4\varepsilon^2}(\phi_0^2 - 1)^2$$

in Comsol

$$\mathbf{F}_{\mathrm{ext}} = \left(\frac{\partial f}{\partial \phi}\right)\nabla\phi$$

External force (due to the disjoining pressure) is a defined source of free energy



to track each interface:
assigning a **marker *c_i*** to each **bubble *i*** and moving the marker like a species in the system, with the same velocity field of the corresponding bubble

transport of diluted species (Fick's eq. and convection term)

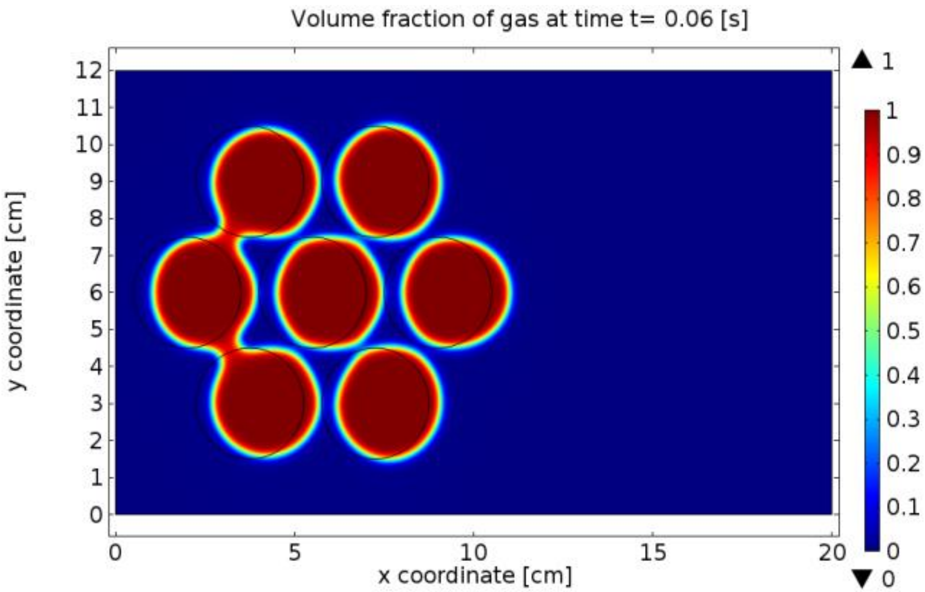
$$\boxed{\frac{\partial c_i}{\partial t} + \nabla \cdot (-D_i \nabla c_i) + \mathbf{u} \cdot \nabla c_i = R_i} \qquad R_i = 0$$

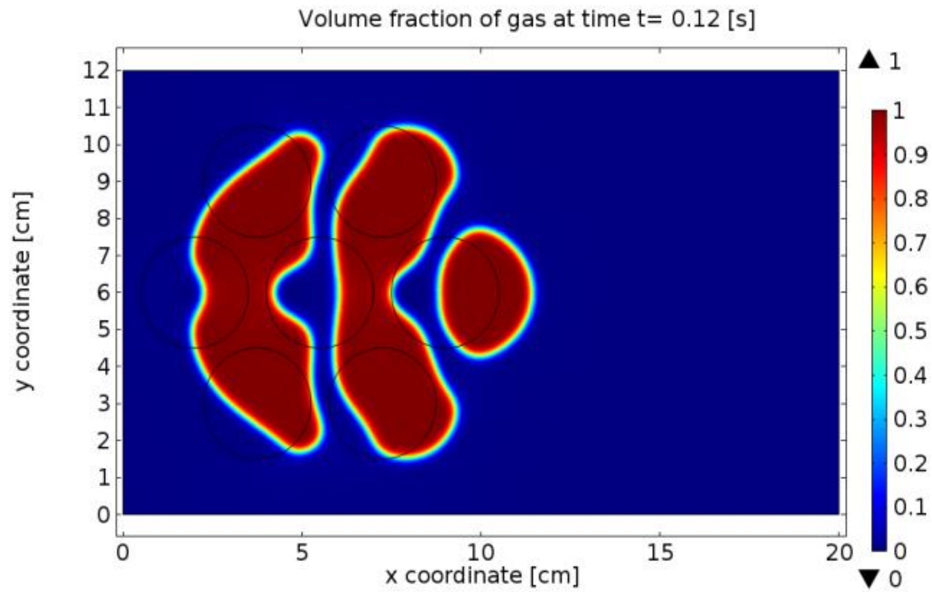
$D_i \approx 10^{-30} m^2/s$ **the marker is only convected**

if $c_i \, x \, c_j > set \;\; value$

disjoining pressure is switched on

Experimental results: without disjoining pressure, bubbles merge

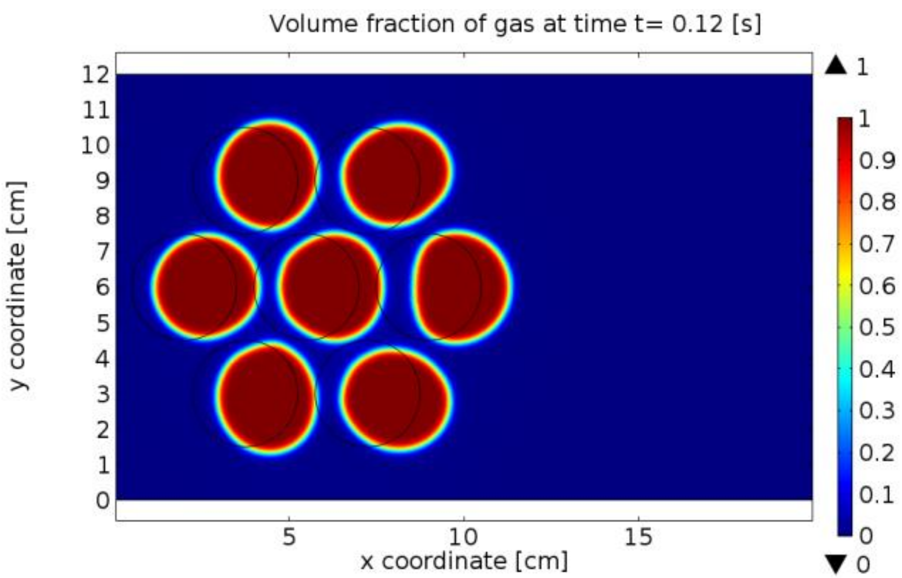


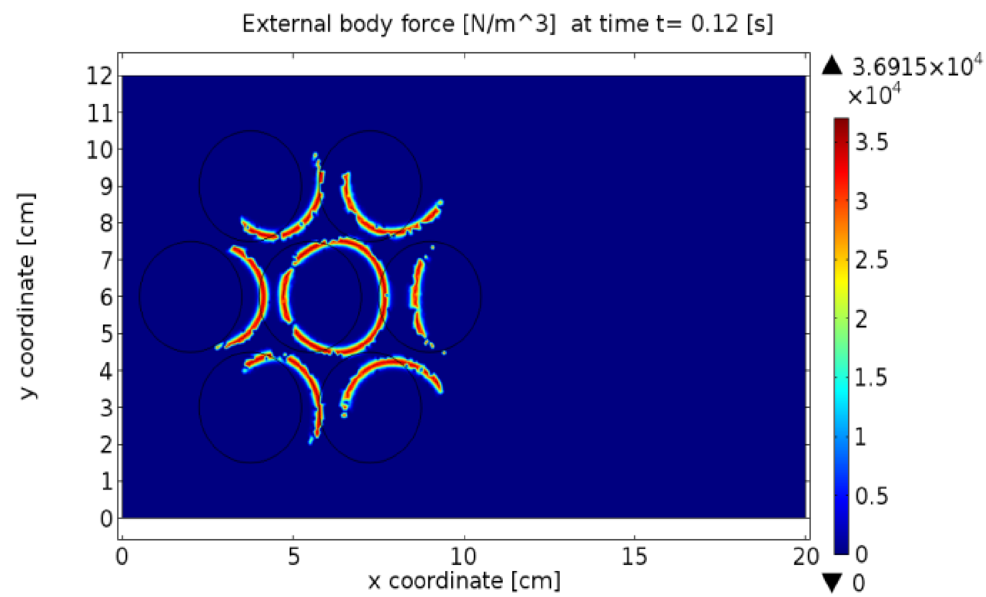


volume fraction of H_2 in a metal foam flowing in a cavity after ***t* =0.06 s** with **disjoining pressure equal to zero**

volume fraction of H_2 in a metal foam flowing in a cavity after ***t* =0.12 s** with **disjoining pressure equal to zero**

Experimental results: with disjoining pressure, stabilization effect





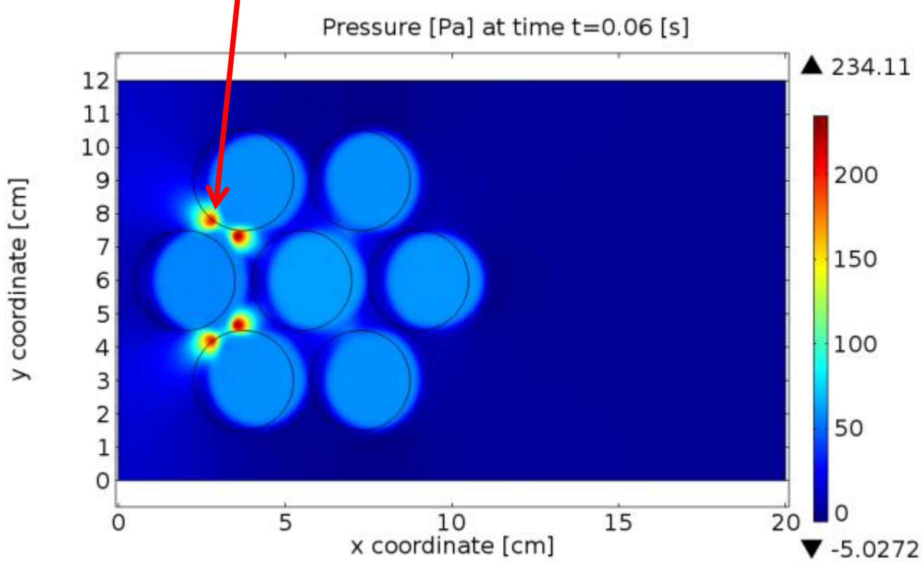
volume fraction of H_2 a ***t* =0.12 s** when the **disjoining pressure sets a repulsive stabilization** effect between the bubbles interfaces

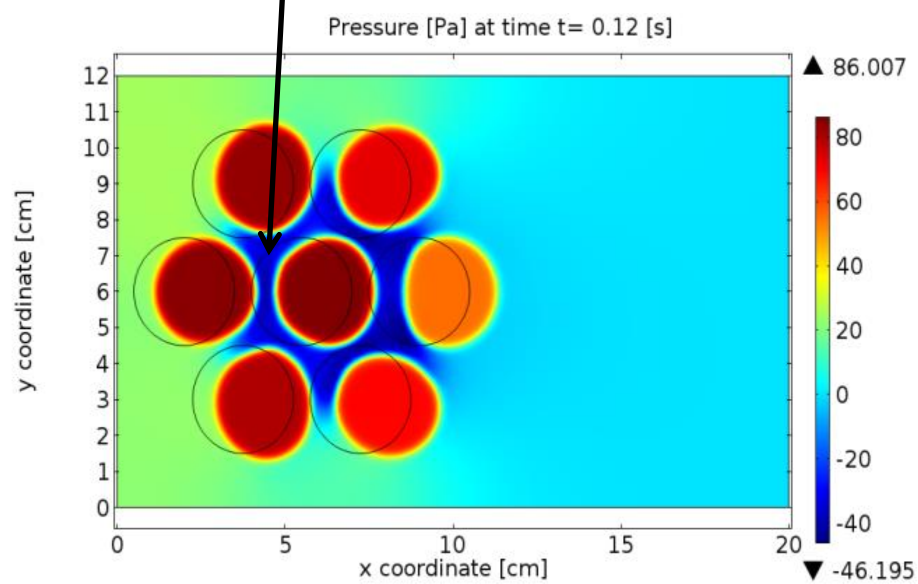
body force due to the disjoining pressure at ***t* =0.12 s** giving **repulsive forces between the bubbles interfaces**

Experimental results: pressure field

without repulsive effects

with repulsive effects due to the disjoining pressure





pressure field in a metal foam flowing in a cavity after *t* =0.12 s with disjoining pressure equal to zero

pressure field in a metal foam flowing in a cavity after *t* =0.12 s when the disjoining pressure sets a repulsive stabilization effect

Conclusions

- A metal foam represented by H_2 gas bubbles and liquid aluminium moving in a laminar flow has been modeled and simulated.

- Surface tension effects have been considered and repulsive forces between neighboring bubbles have been expressed through the disjoining pressure.

- The model uses a formulation of the disjoining pressure in the framework of the phase field method. Fundamental mechanisms due to surface tension effects and disjoining pressure have been reproduced.

- The numerical results show that diffuse interface methods are effective to model this kind of complex phenomena.

- The above results are encouraging for our under way researches in the modeling of metal foaming processes.

Many thanks for your attention.

Thanks also to the organizers of

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