Modeling of Transport Phenomena in Metal Foaming

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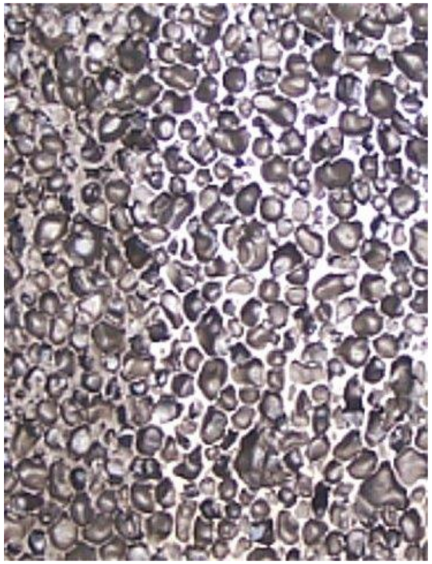
Presentation overview



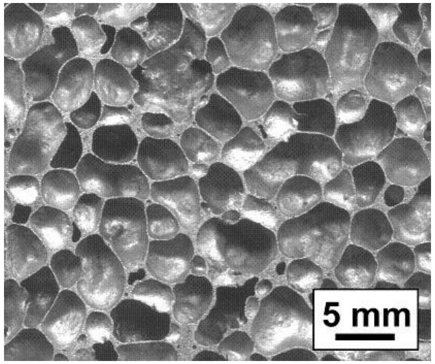
- Introduction
- Indirect foaming via precursor
- Bubble expansion by mass diffusion
- Mathematical model in Comsol Multiphysics
- Numerical results
- Conclusions

Metal foams

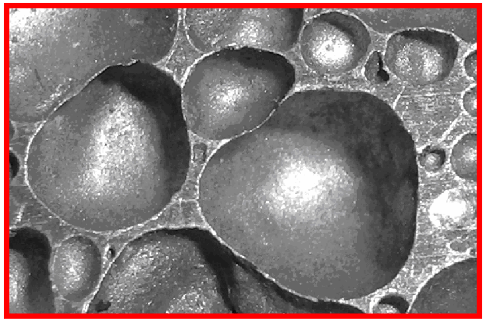
Uniform gas-liquid mixture (gas-metal or gas-alloy) in which the volume fraction of the liquid phase is small (10-20%: wet foam, <10% dry foam)

D.J. Durian (UCLA): ...*a random packing of bubbles*...
or ...*a most unusual form of condensed matter*...

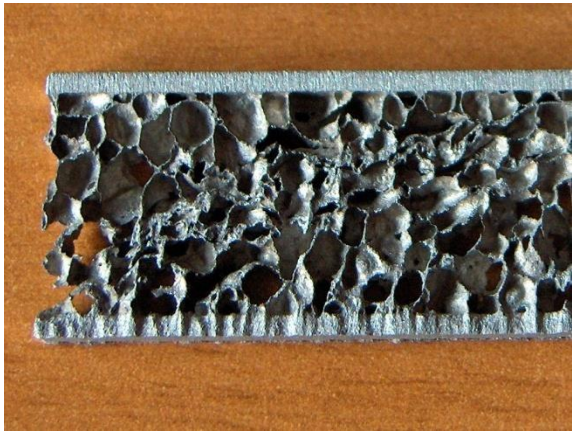
melted Al and H_2 gas



Al metal foam

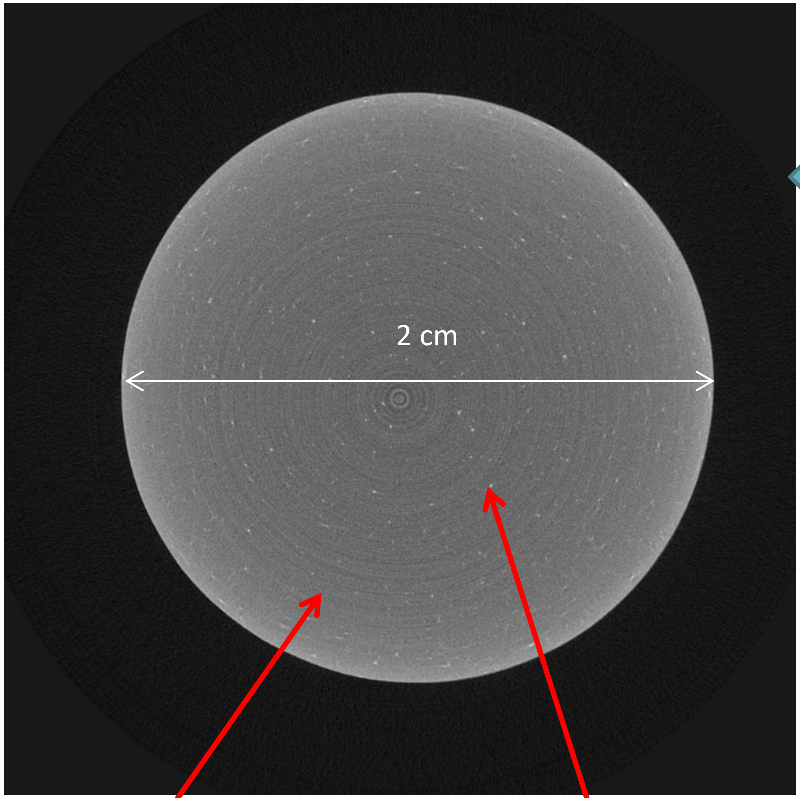


solidified metal foam



Indirect foaming via precursor: precursor

solid precursor



grey areas : Al alloy

white areas : TiH_2 foaming agent

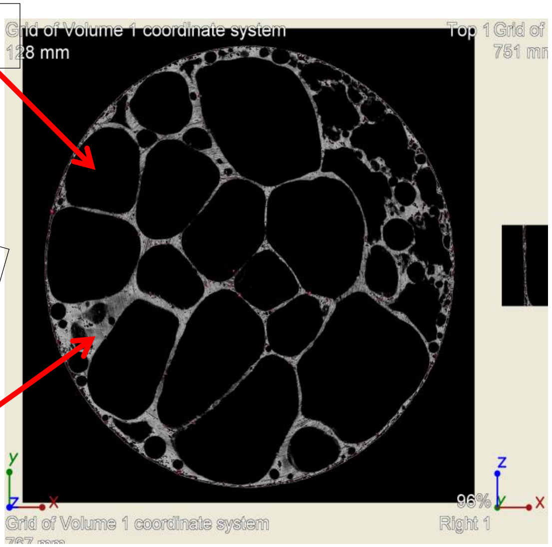
Precursor : compacted Al (or Al alloy) and foaming agent

- mixing of a foaming agent powder (TiH_2) and the base metal powder (Al or Al alloy)
- cold compacting the powder
- extrusion of the pre-compacted billet in order to obtain a **precursor material** whose density is close to that of the base metal

foamed precursor

H_2 bubble

after having been heated and foamed

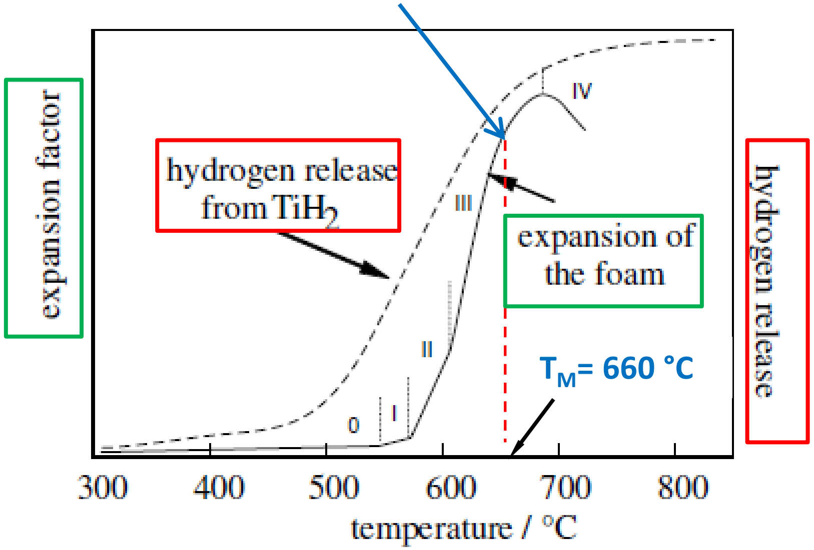


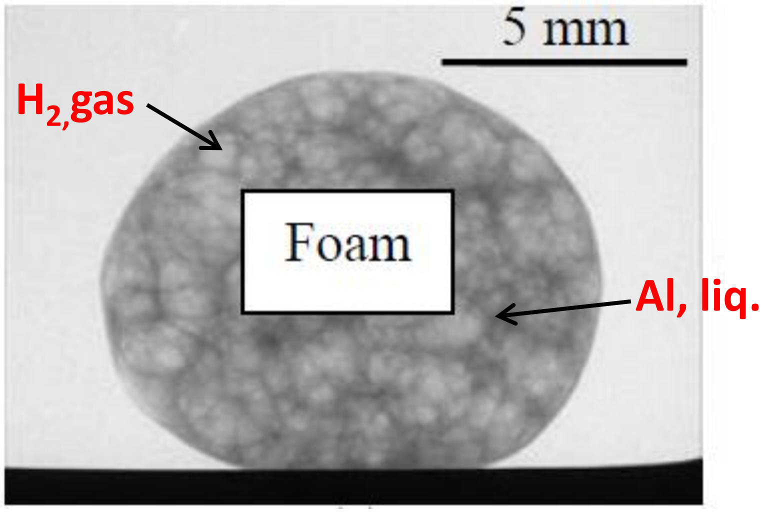
Al (or Al alloy)

Images by X ray computed µ-tomography

Foaming process

large foam expansion, Al is largely melted (T_M= melting temperature)





X ray image of a foamed precursor

- 0: thermal expansion of the metal
- I: bubble nucleation in solid metal/ TiH2 decomposes, H_2 gas starts to be released
- II: bubble expansion (small) in the semi-solid range ($T<T_M$)/ much H_2 gas is released
- **III: bubble expansion in a metal, largely melted ($T \approx T_M$)/ H_2 gas is highly released**
- IV: initial foam collapse (can be avoided by foam solidification)

Indirect foaming via precursor: physical phenomena

Foaming is a complex phenomena:

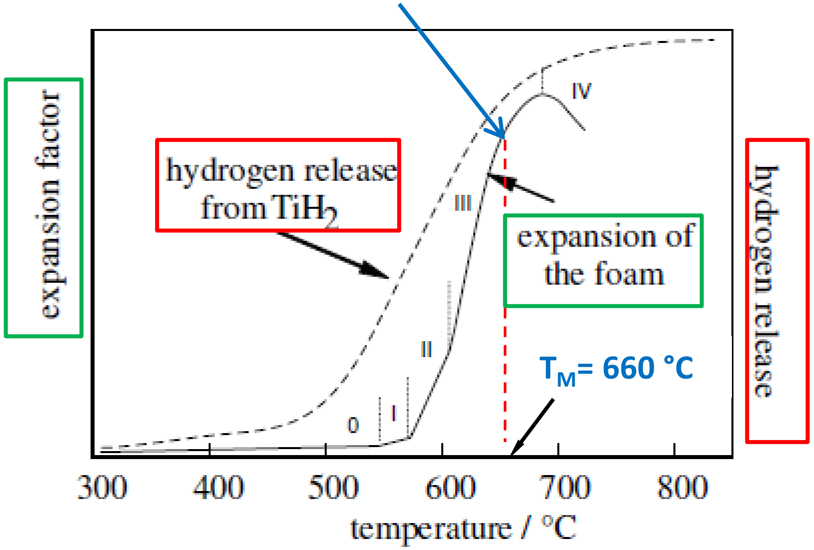
- simultaneous mass, momentum and energy transfer mechanisms
- several physical phenomena on interfaces, interface motion
- **bubble expansion**, dynamics, coarsening, rupture
- other aspects (drainage, mould filling, geometry)
- difficulty for experimental measurements (foams are hot, opaque, etc.)

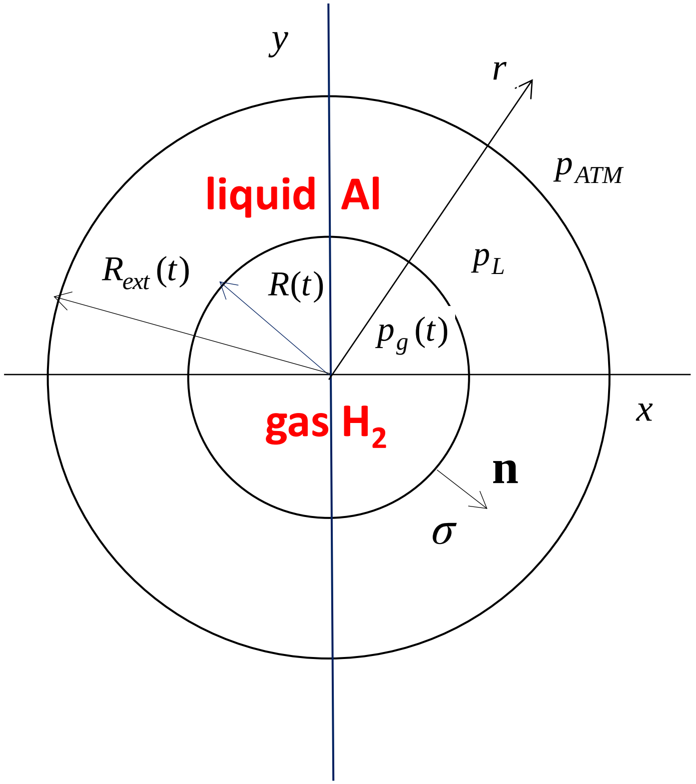
Bubble expansion by mass diffusion

step III- bubble expansion when Al is largely melted (T_M= melting temperature):

- H_2 gas is highly released

- H_2 dissolves in the aluminium and insoluble gas diffuse towards existing bubbles or nuclei, which causes them to inflate.



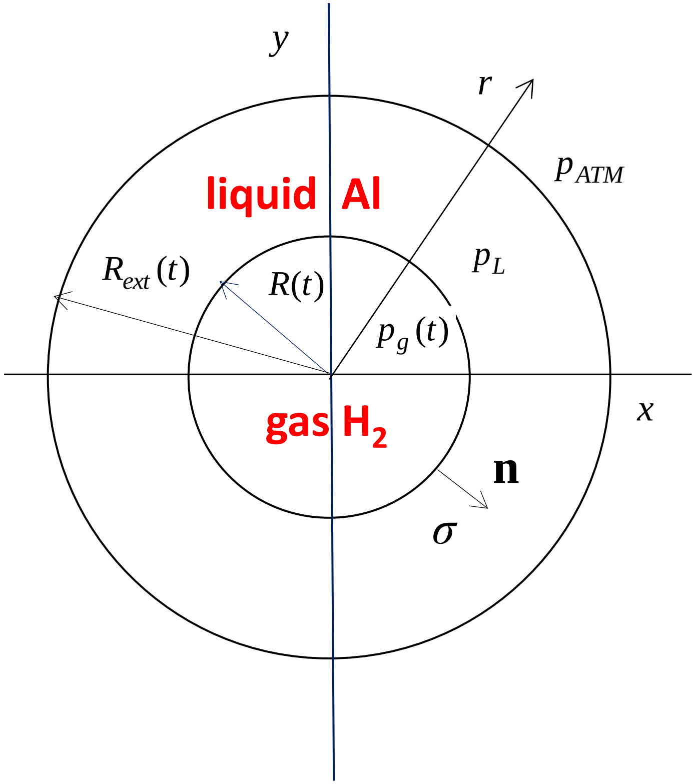


➡ **expansion of a single H_2 bubble in a melt of aluminium**

Bubble expansion by mass diffusion

step III- Physical model

- the 2D system (disk) is isothermal at T_M, gravity is absent
- the melted Al is considered as an incompressible Newtonian liquid of constant viscosity
- at the boundary of the system the pressure is fixed at atmospheric pressure
- H_2 (ideal gas) is the only gas in the bubble; equilibrium concentration at the gas-liquid interface is given by the **Sievert's law**
- the thermodynamical equilibrium at the gas-liquid interface between the hydrogen partial pressure in the gas bubble and the dissolved hydrogen in liquid Al is expressed by the **Gibbs-Thomson equation (surface tension effects)**



expansion of a single H_2 bubble in a melt of aluminium

Bubble expansion by mass diffusion

(Atwood *et al*. 2000, Gibbs-Thompson equation)

presence of surface tension effects

↓

$$\boxed{C_H^* = S_H^L \exp\left(\frac{\sigma V}{R(t)\,\Re\,T}\right)}$$

concentration of H_2 at the interface between gas bubble/ Al melt

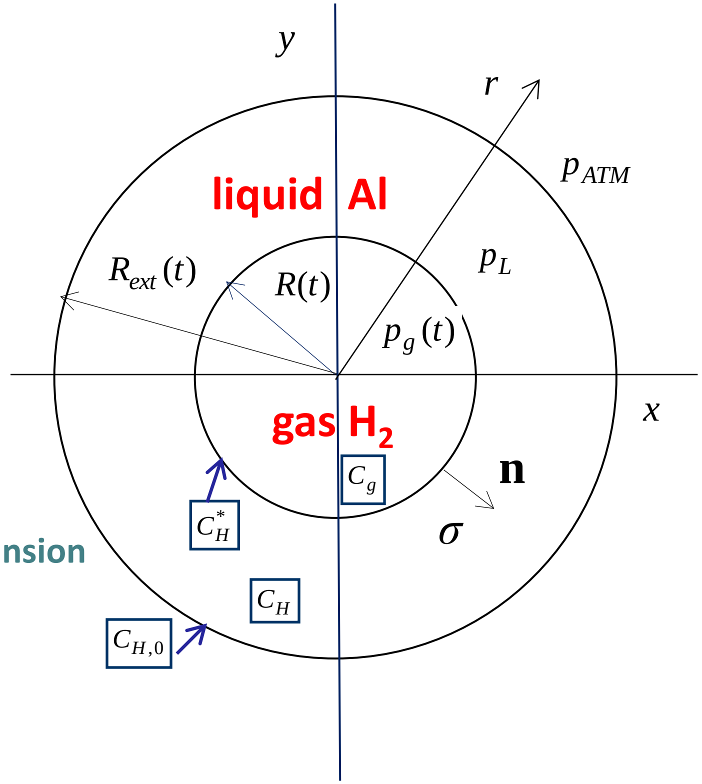
$$\boxed{\log S_H^L = -\frac{2760}{T} + 2.796, \quad \text{ml/100g STP}}$$

solubility of H_2 in Al

$$\boxed{\left(C_g - C_H^*\right)\frac{dR(t)}{dt} = D_H\left(\frac{\partial C_H}{\partial r}\right)_{r\,=\,R(t)}}$$

change of $R(t)$ → **bubble expansion**

$$C_g = \frac{p_g}{\Re\,T}, \qquad p_g = p_L + \frac{\sigma}{R(t)}$$



coupled to:

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

$$\boxed{\frac{\partial C_H}{\partial t} + \nabla\cdot\left(-D_H\nabla C_H\right) + \mathbf{u}\cdot\nabla C_H = R_H}$$

$$R_H = 0$$

at time t=0, in the melt: $C_H = C_{H,0} > C_H^*$

for all the times t, on the external surface: $C_H = C_{H,0}$

Mathematical model in Comsol Multiphysics

Former equations coupled to (Chemical Reaction Engineering and CDF modules)

continuity

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

momentum transfer

flow is laminar

$$\rho\frac{\partial\mathbf{u}}{\partial t}=\nabla\bullet[-p\mathbf{I}+\eta(\nabla\mathbf{u}+(\nabla\mathbf{u})^T)-\frac{2\eta}{3}(\nabla\bullet\mathbf{u})\mathbf{I}]+\mathbf{F}_{st}+\mathbf{F}_{ext}+\mathbf{F}$$

interface movement (phase field ϕ)

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

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

help variable ψ

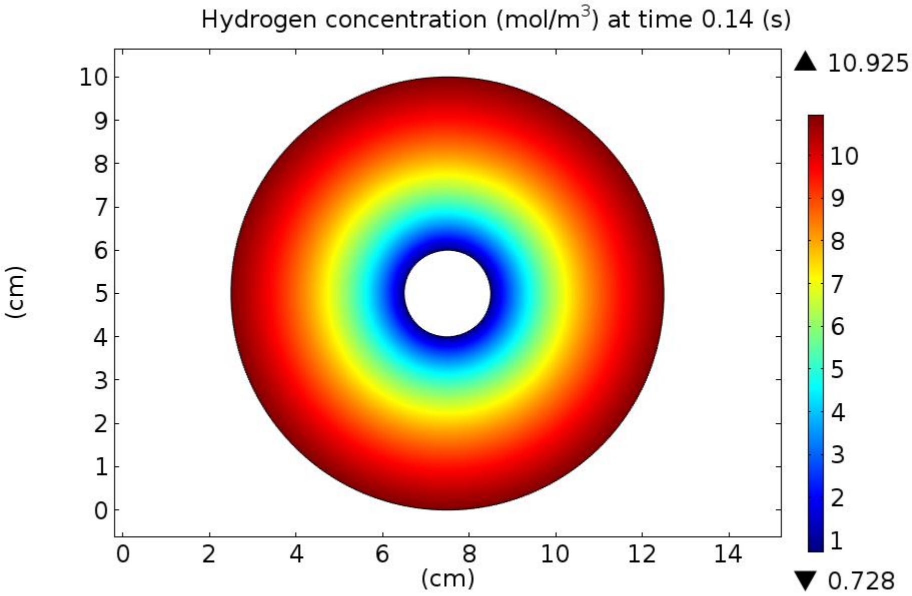
$$\mathbf{F}_{\mathrm{st}}=\left(G-\frac{\partial f}{\partial\phi}\right)\nabla\phi$$

Surface tension force

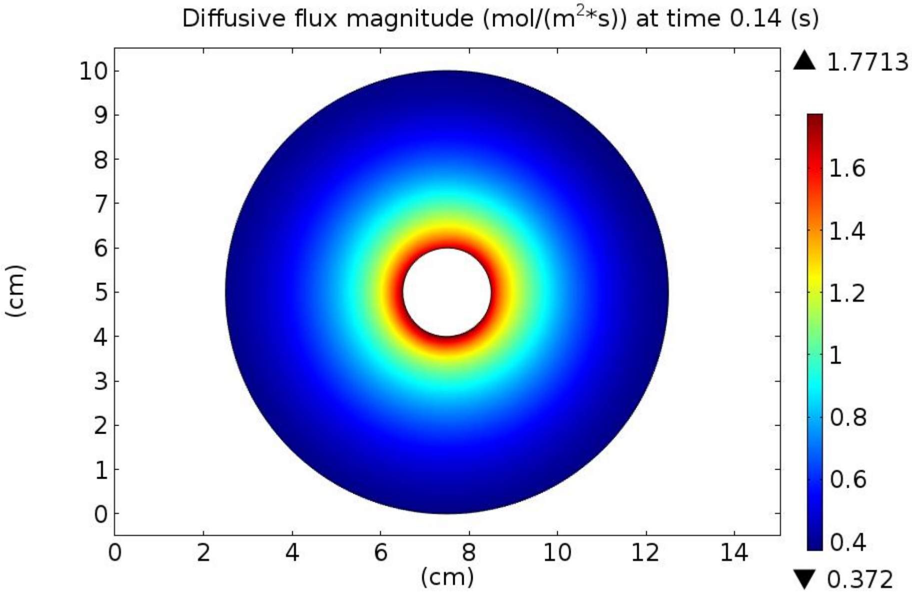
and coupled to Global ODEs and DAEs User Interface to solve

$$\left(C_g-C_H^*\right)\frac{dR(t)}{dt}=D_H\left(\frac{\partial C_H}{\partial r}\right)_{r=R(t)}$$

Numerical results

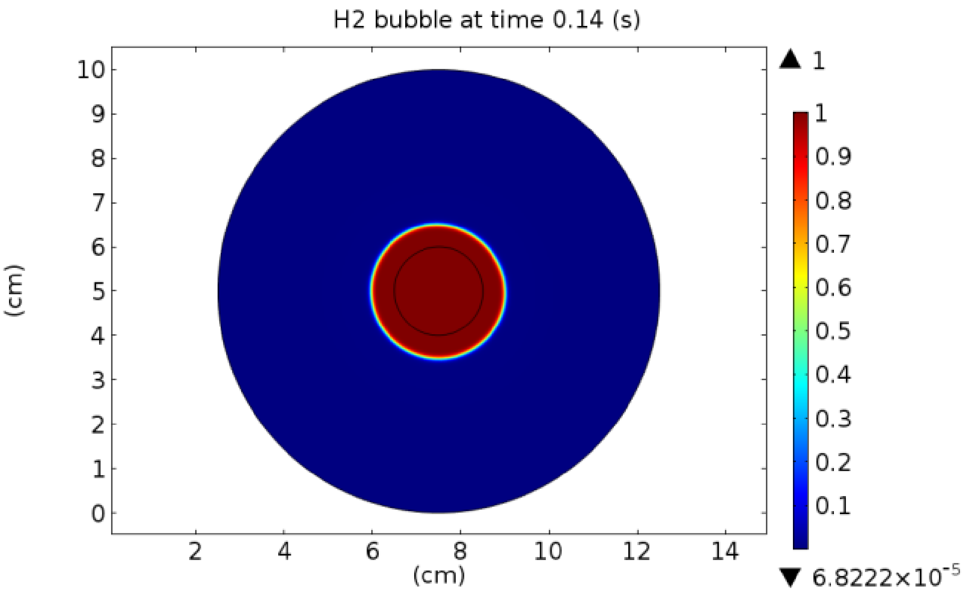


values of **hydrogen concentration** in the shell of aluminium melt ($C_{H,0}$ = 15xC^*_H, $D_H = 10^{-3}$ m^2/s)

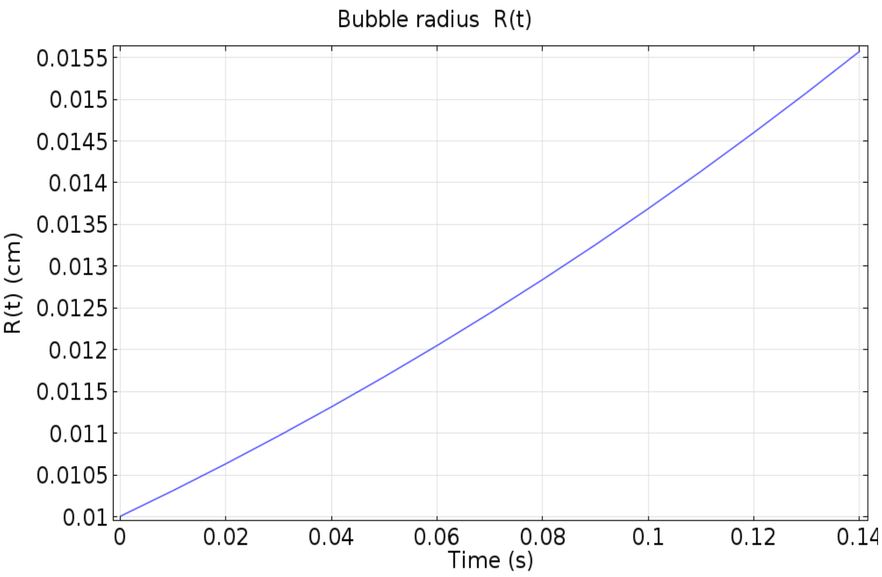


values of the **diffusive flux magnitude of hydrogen** in the shell of aluminium melt ($C_{H,0}$ = 15x C^*_H, $D_H = 10^{-3}$ m^2/s)

Numerical results

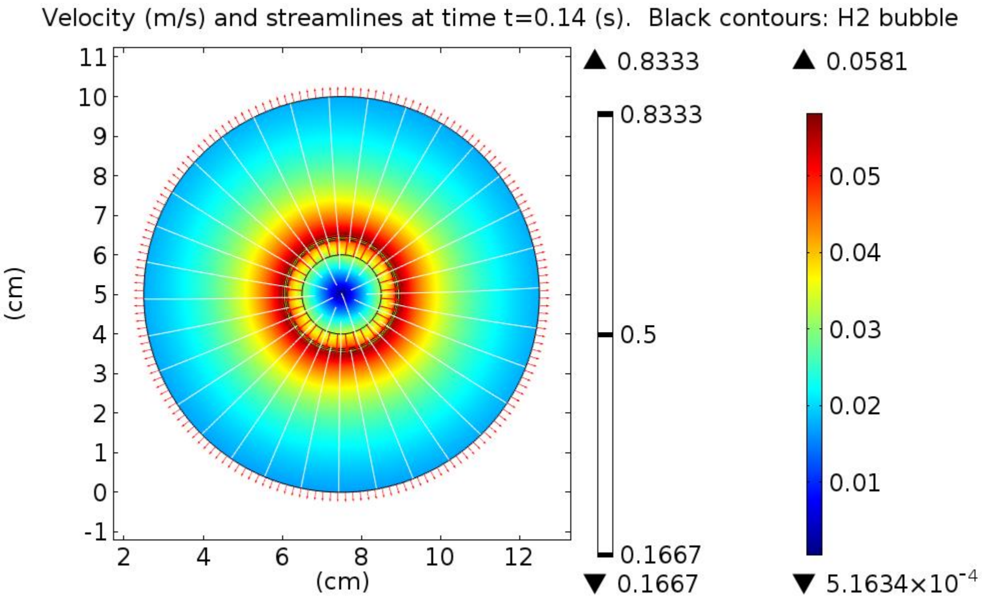


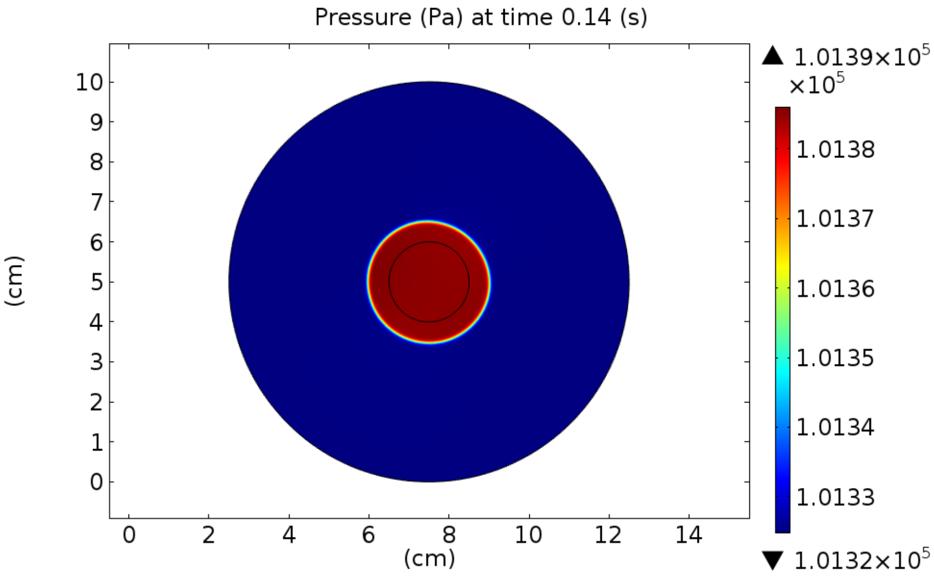
position of the H_2 **gas-liquid aluminium interface** after *t* = 0.14 s ($C_{H,0} = 15 \times C^*_H$, $D_H = 10^{-3}$ m^2/s)



plot of the gas bubble **time dependent radius** ($C_{H,0} = 15 \times C^*_H$, $D_H = 10^{-3}$ m^2/s)

Numerical results


Velocity (m/s) and streamlines at time t=0.14 (s). Black contours: H2 bubble


Pressure (Pa) at time 0.14 (s)

velocity field and **streamlines** in the H_2 bubble and aluminium shell after *t* =0.14 s; position of the actual H_2 **gas-liquid aluminium interface** is also shown (contours)

pressure field in the H_2 bubble and aluminium shell after *t* =0.14 s

Conclusions

- A computational model considering mass transfer phenomena coupled to the growth and motion of gas bubbles in the liquid metal has been proposed.

- Gas diffusion in the liquid has been simulated by applying the Fick's law, convective transport and including surface tension effects on the gas-liquid interface.

- The computations simulate satisfactorily mass transfer, bubble expansion, interface movement and fluid flow and show that the phase field method, for capturing the phase interface, can be effective.

- In this way other physical mechanisms of foaming could be included in a future more comprehensive model.