MUSP

Macchine Utensili e Sistemi di Produzione

# Multiphysics modeling of a gas bubble expansion

Bruno Chinè[1,2] , Michele Monno[1,3]

[1] Laboratorio MUSP, Piacenza, Italy; [2] ITCR, Cartago, Costa Rica; [3] Politecnico di Milano, Italy

bruno.chine@musp.it

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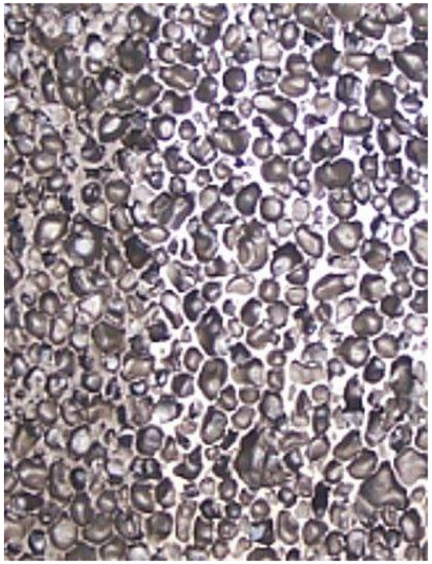
# Presentation overview



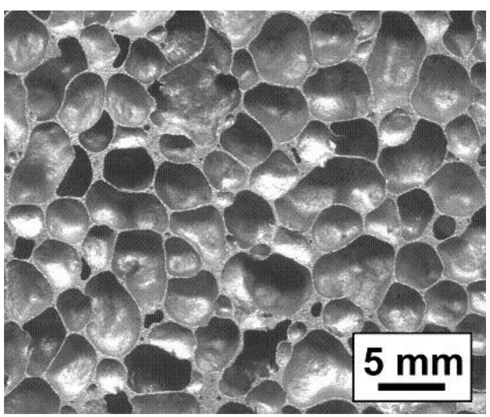
- Introduction, metal foams
- Bubble expansion model
- Simulations by Comsol Multiphysics
- Results
- Conclusions

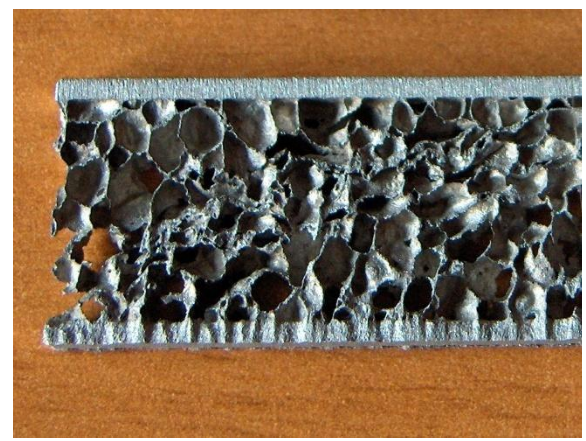
# Metal foams

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...*

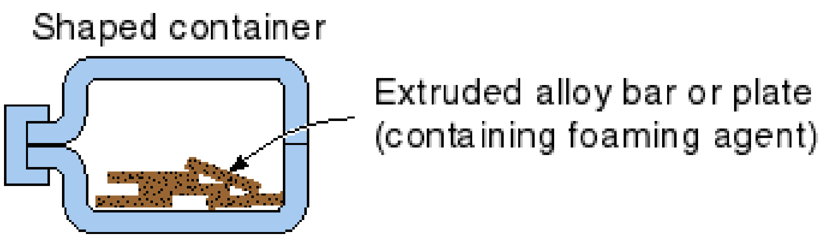
solidification → solidified metal foam

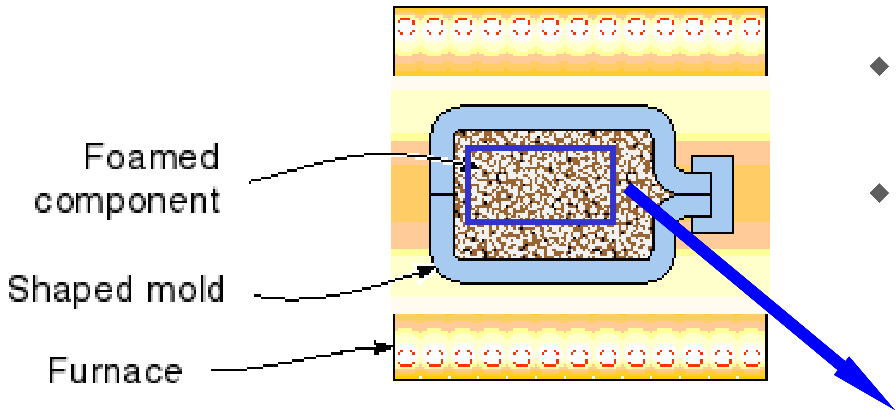


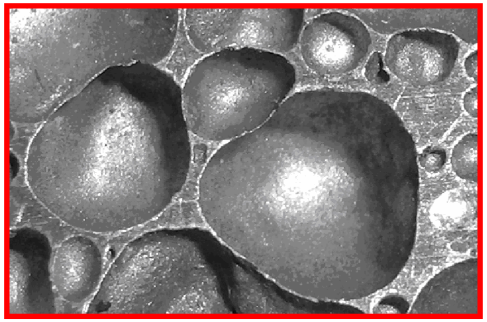
# Process and bubble growth

## Shaped mould




- chopping of the **precursor** material in small pieces
- placing inside a sealed split mould
- heating to a temperature a little above the solidus temperature of the alloy
- foaming agent decomposition and foam formation
- cooling and extraction



# A bubble expansion model

The model starts from a previous work of the same authors, who simulated a bubble growth with Comsol, modelling the bubble as a disk in 2D.

Now we extend the model to a spherical bubble in 3D, applying after axial symmetry condition to reduce the computational effort.

Moreover, more realistic values of surface tension, density and viscosity are set for the $H_2$-aluminium system.

In order to obtain convergence: a step function for the initial pressure difference in the system and mesh refinement for the transient solution are introduced in the model.

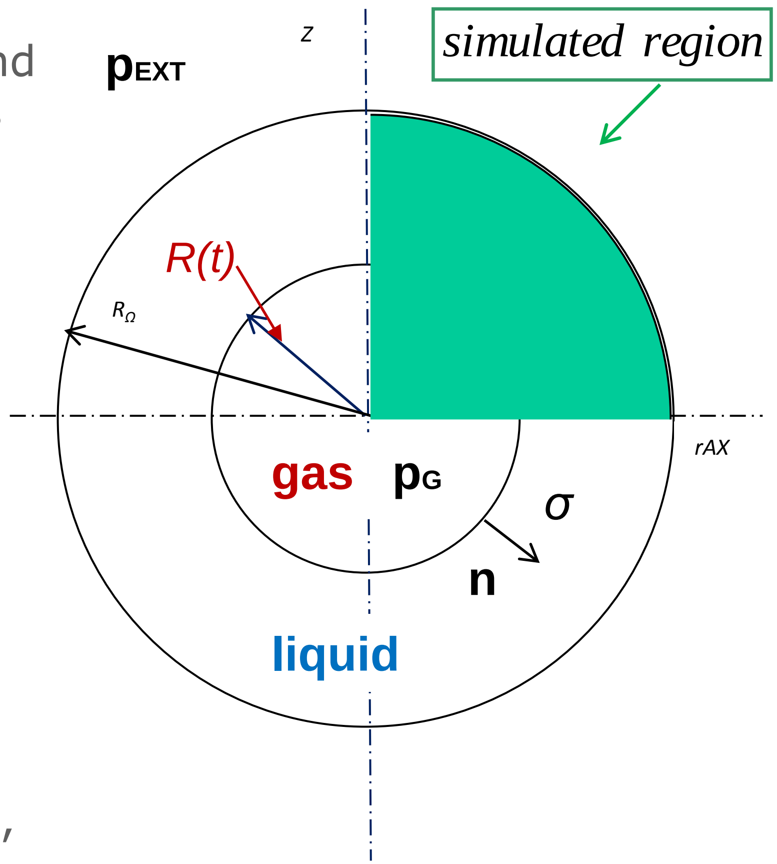
# A bubble expansion model

Starting with a spherical bubble in 3D and using a system of cylindrical coordinates ($r_{AX}$, $\varphi$, $z$) and axial symmetry around z:

⇨ 2D

since $r_{AX}$ is also a symmetry axis, we study the region:

$$0 \le r_{AX} \le R_\Omega, \quad 0 \le z \le R_\Omega$$

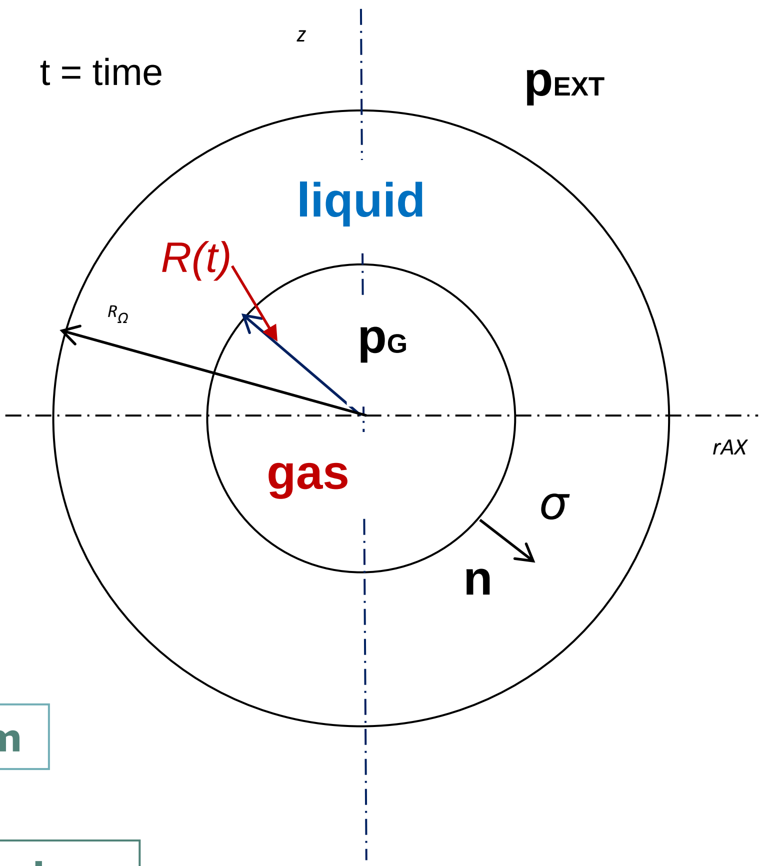



- transient bubble expansion
- isothermal, no mass diffusion: growth is only driven by a pressure difference, surface tension $\sigma$ effects are considered
- gas follows the ideal gas law $pV = n\Re T$, liquid is incompressible, fluids are immiscible

# Level set interface

$$R_{eq} = \frac{2\sigma}{p_G - p_{EXT}}$$

**without flow at time t**




## Comsol Multiphysics 4.2 :

Two Phase Flow, Level Set interface, Weakly-Compressible:

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

**continuity**

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

**momentum**

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \bullet \nabla \phi = \gamma \nabla \bullet [\varepsilon \nabla \phi - \phi(1-\phi)\frac{\nabla \phi}{|\nabla \phi|}]$$

**level set**

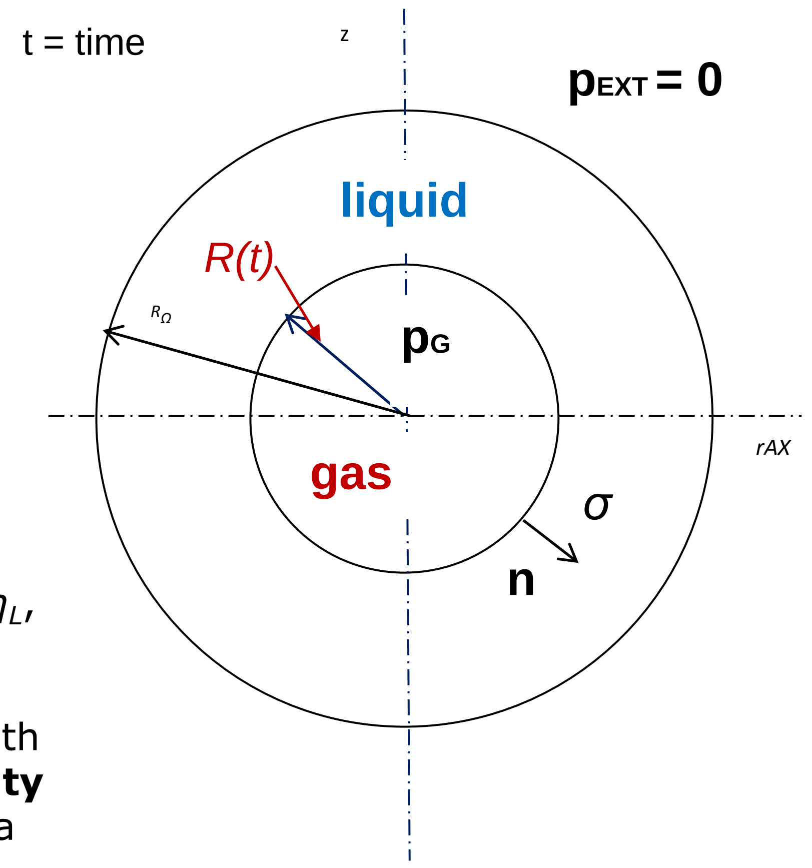
# Equation for gas density

**gas density is modelled as:**

$$\rho_G(t) = \frac{\rho_{G,0}}{\left\{1 + \frac{1}{4\eta_L}\left[p_{G,0} - (p_{EXT,0} + \frac{2\sigma}{R_0})\right] t\right\}^3}$$

$\eta_L$, dynamic viscosity of the liquid

**(Gniloskurenko et *al*. , 2002)**




depending on the values of $p_G$ , $p_{EXT}$ , $\sigma$, $R_0$ and $\eta_L$, the expansion could be very fast

by means of Gniloskurenko eq., a gas bubble with $R_0$ = 0.01 m, would obtain an **interface velocity** of ~ 0.25 m/s for a pressure difference of 10 Pa and $\eta_L$ =$10^{-3}$ Pa·s

➡ R= 0.02 m in 0.04 s

# Simulations: properties and parameters

| Magnitude | Symbol | Value |
|---|---|---|
| Universal gas constant | | 8.314 J/(mol·K) |
| Gas molar mass | $M$ | 2 g/mol |
| Gas density (Hydrogen) | $\rho_G$ | ideal gas and eq. of Gniloskurenko et *al.* |
| Liquid density (Aluminium) | $\rho_L$ | 10 kg/m$^3$ |
| | | 2.4 kg/m$^3$ |
| Gas viscosity | $\eta_G$ | 10$^{-3}$ Pa·s |
| Liquid viscosity | $\eta_L$ | 10$^{-1}$ Pa·s |
| | | 4.5x10$^{-3}$ Pa·s |
| Surface tension coefficient | $\sigma$ | **0.95 N/m** |
| Initial bubble radius | $R_0$ | 10$^{-2}$ m |
| Initial bubble pressure | $p_{G,0}$ | 400 Pa |
| | | 190.1 Pa |
| Ambient pressure | $p_{EXT}$ | 0 Pa |
| Constant temperature | $T$ | 933 K |

$$\max \frac{\rho_L}{\rho_{G,0}} \cong 9x10^4$$

| Magnitude | Symbol | Value |
|---|---|---|
| Max element size of the mesh | - | 10$^{-4}$ m |
| Time stepping | - | set by the solver |
| Relative tolerance | - | 10$^{-3}$ s |
| Absolute tolerance | - | 10$^{-4}$ s |
| Interface thickness | $\varepsilon$ | 8x10$^{-5}$ m |
| Reinitialization | $\gamma$ | 0.5 ÷ 5 m/s |

mesh : $8x10^4$ triangle elements

$5x10^5$ DOF

Direct solver PARDISO (*Comsol Multiphysics* 4.2)

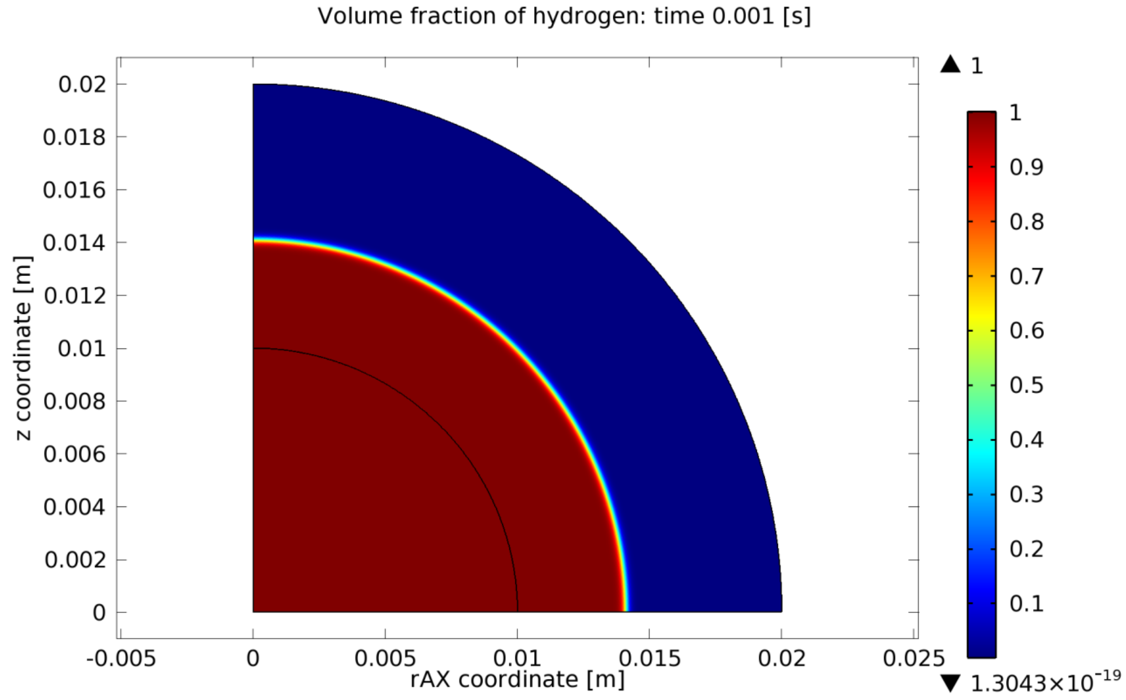
$$\text{stepsize} = 10^{-3} \div 10^{-5}\, s,$$

$$\text{solution time} \cong (2 \div 3)x10^4\, s\, (f(t_{fin}))$$

# Results

## bubble expansion

$$p_{G,0} = 400\,\text{Pa},\ \rho_L = 10\,\text{kg/m}^3,\ \mu_L = 10^{-1}\,\text{Pa.s}$$



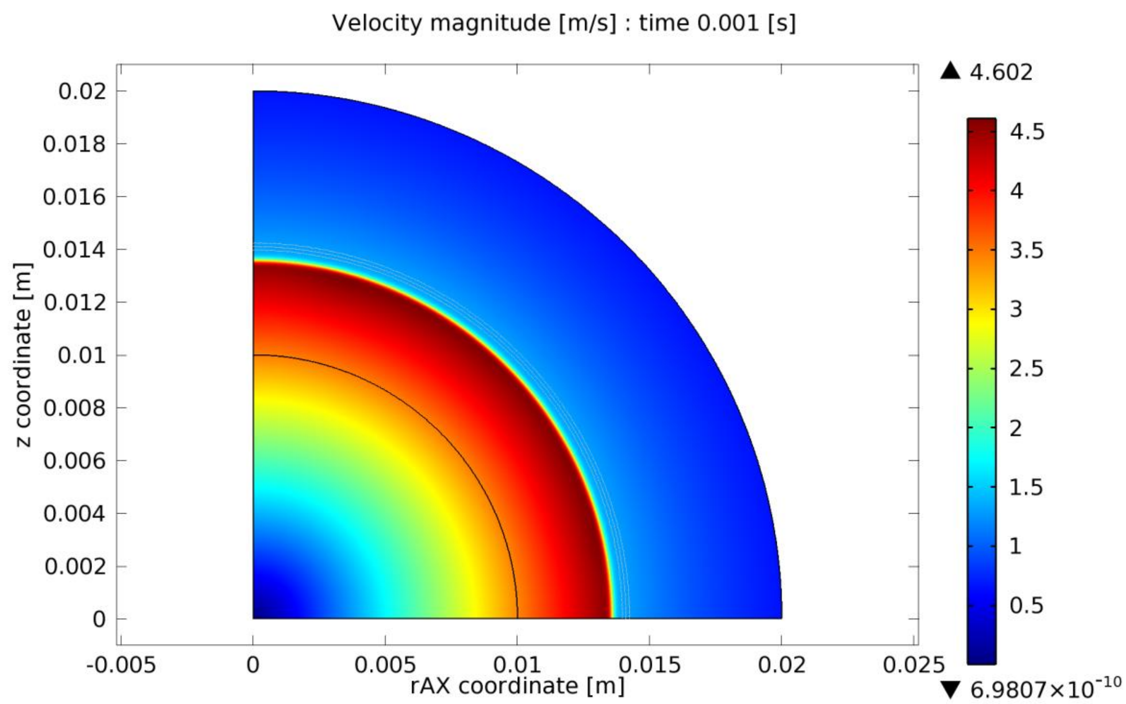

$$\nu = \frac{\mu}{\rho} = 10^{-2}\ \text{m}^2/\text{s}$$

$$\text{Re} \cong 5.3$$

# Results

## bubble expansion

$$p_{G,0} = 400\,\text{Pa},\ \rho_L = 10\,\text{kg/m}^3,\ \mu_L = 10^{-1}\,\text{Pa.s}$$

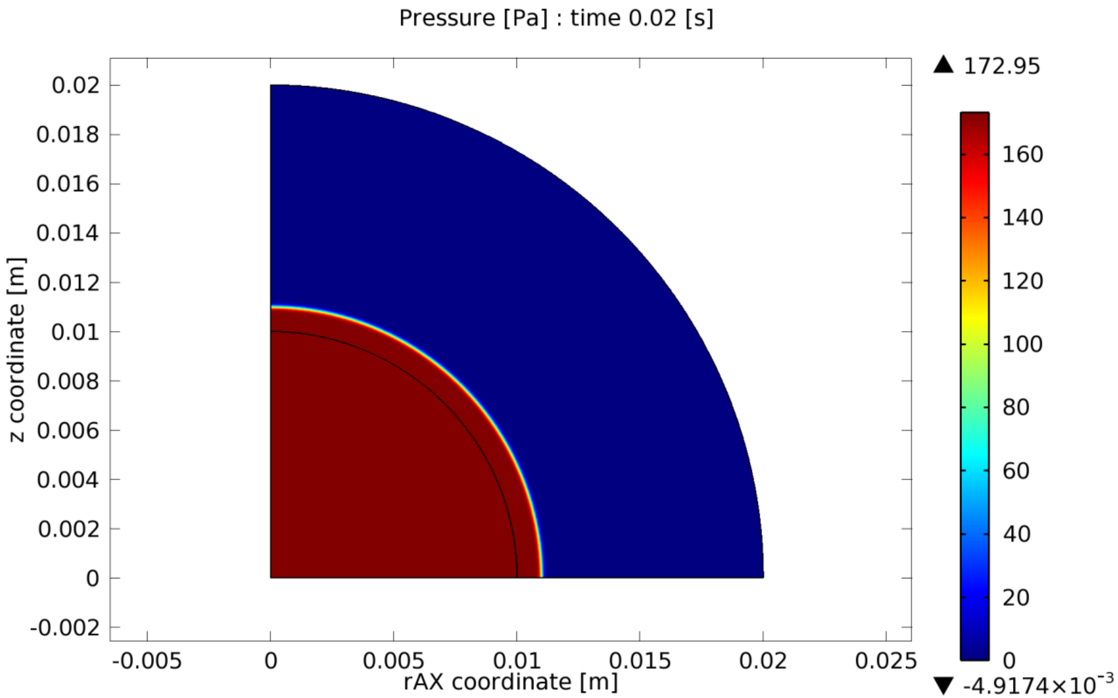



$$\nu = \frac{\mu}{\rho} = 10^{-2}\,\text{m}^2/\text{s}$$

$$\text{Re} \cong 5.3$$

## bubble expansion

$$p_{G,0} = 190.1\,\text{Pa},\ \rho_L = 10\,\text{kg/m}^3,\ \mu_L = 4.5x10^{-3}\,\text{Pa.s}$$



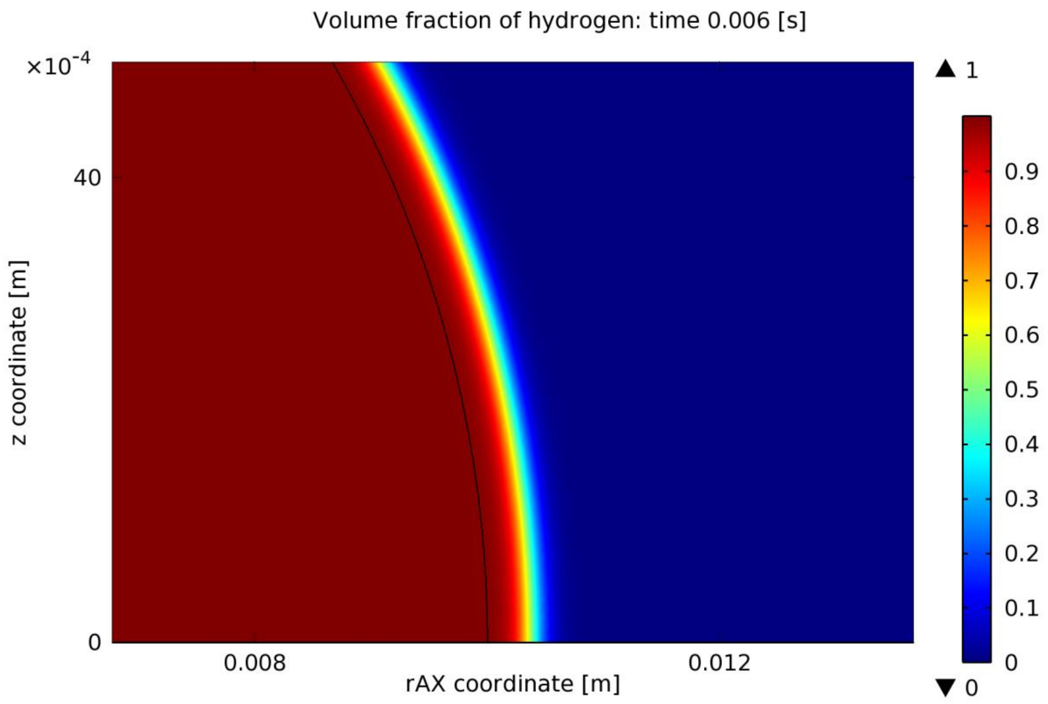

$$\nu = \frac{\mu}{\rho} = 4.5^{-4}\ \text{m}^2/\text{s}$$

$$\text{Re} \cong 1.2$$

# Results

## bubble expansion

$$p_{G,0} = 190.1\,\text{Pa},\ \rho_L = 2.4x10^3\ \text{kg/m}^3,\ \mu_L = 4.5x10^{-3}\ \text{Pa.s}$$

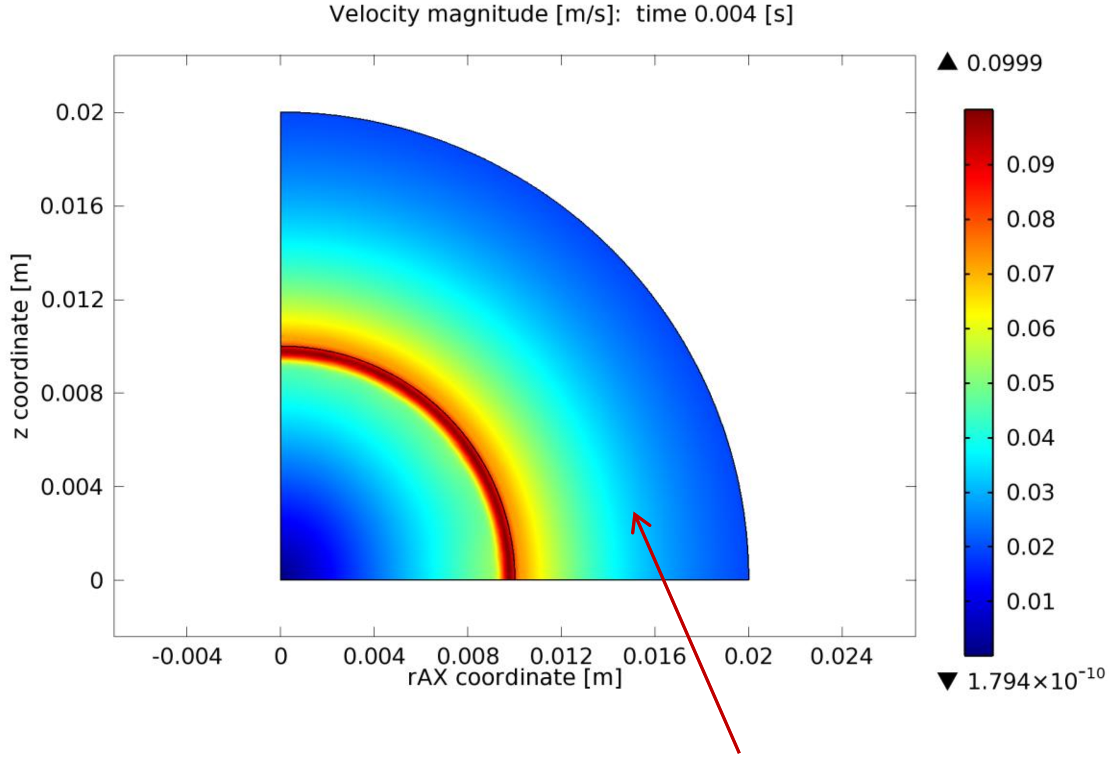



$$\nu = \frac{\mu}{\rho} \cong 1.9x10^{-6}\ \text{m}^2/\text{s}$$

$$\text{Re} \cong 293$$

## bubble expansion

$$p_{G,0} = 190.1\,\text{Pa},\ \rho_L = 2.4x10^3\ \text{kg/m}^3,\ \mu_L = 4.5x10^{-3}\ \text{Pa}\cdot\text{s}$$




$$\nu = \frac{\mu}{\rho} \cong 1.9x10^{-6}\ \text{m}^2/\text{s}$$

$$\text{Re} \cong 293$$

# Conclusions

- The model computes bubble expansion with flow in gas and liquid regions. Gas pressure drives the growth.
- A weakly-compressible model, coupled to a level set equation, allows to capture the interface. Surface tension for the system $H_2$- aluminium is considered.
- Realistic values of densities and viscosities for both the $H_2$ and the aluminium are set: step function for the initial pressure difference in the system, and mesh refinement for the transient solution are used.
- To improve our future work, we foresee:
  - to include mass diffusion and heat transfer in the model;
  - to take into account more bubbles in the system in order to consider their interactions.

# References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# *Many thanks for your attention.*

# *Thanks also to the organizers of*

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