# Nucleate Boiling and Microlayer Formation

## Numerical Methods for Fluid Mechanics - MEC655

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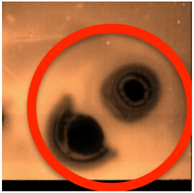
# Introduction

- The transport of latent heat for bubbles in boiling.
- A primary mode of heat transfer in Boiling Water Reactors (BWR)
- Also active in various domains like : refrigeration and air-conditioning, chemical thermal processing, etc.



# Phenomenon

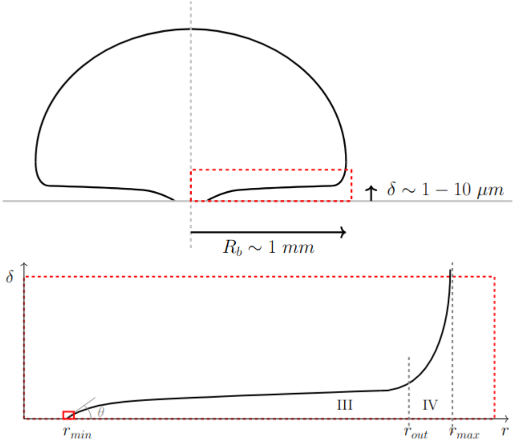



Figure 1: Microlayer formation in nucleate boiling [1]

## Assumptions and Model

- Thermal effects are neglected.
- We consider the phenomenon to be axisymmetric.
- Microlayer evaporation is ignored ($\tau_2 \approx 1$ - 10 ms). The object of study is the microlayer formation ($\tau_1 \approx 10$ - 100 $\mu$s).

- Therefore, this model does not contemplates phase change.
- Modelling is done using a source term $S_v$ in the mass conservation equation; which depends on $U_b$, the growth rate of the bubble.

$$U_b = \sqrt{\pi h_{fg} \rho_\nu \nabla T_{sat} / (7 \rho_l T_{sat})} \tag{1}$$

## Assumptions and Model

In view of this, the equations that govern the phenomenon are:

$$\rho(\partial \vec{U}/\partial t + \vec{U} \cdot \nabla \vec{U}) = -\nabla p + \nabla \cdot (2\mu \bar{\bar{D}}) + \sigma\kappa\sigma_s \vec{n} + \vec{F}_{external} \quad (2)$$

$$\partial\rho/\partial t + \nabla \cdot (\rho \vec{U}) = S_v \quad (3)$$

And for the Volume-Of-Fluid method:

$$\partial C\rho/\partial t + \nabla \cdot (C\rho \vec{U}) = S_v \quad (4)$$

## Assumptions and Model

Finally, for a constant bubble growth rate, $S_v$ is modelled as:

$$S_v = \frac{3U_b}{(R_{b,0} + U_b t)} \tag{5}$$

Therefore, the source term only depends on:

- $U_b$, the bubble's growth rate.
- $R_{b,0}$, the initial bubble radius.
- $t$, the time.

# Nondimensionalization

For the nondimensionalization, a reference scale for space, $r_c$; and time, $t_c$, are defined:

$$r_c = \frac{\mu_l}{(\rho_l U_b)} \qquad t_c = \frac{\mu_l}{(\rho_l U_b^2)} \tag{6}$$

And applying the Vaschy-Buckingham theorem, we obtain the following dimensionless groups:

$$\Pi_1 = \delta / r_c = \delta^* \qquad \Pi_4 = r / r_c = r^* \qquad \Pi_6 = \theta$$
$$\Pi_2 = \mu_l / \mu_\nu = \mu^* \qquad \Pi_5 = t / t_c = t^* \qquad \Pi_7 = Ca = \mu_l U_b / \sigma$$
$$\Pi_3 = \rho_l / \rho_\nu = \rho^*$$

# Nondimensionalization

Finally, applying the reference scales to the conservation equations (2) and (3), we obtain a dimensionless reformulation of the physical parameters:

Table 1: Nondimensional reformulation of the physical parameters.

| $\rho_1$ | $\rho_2$ | $\mu_1$ | $\mu_2$ | $\sigma$ |
|---|---|---|---|---|
| 1 | $\frac{1}{\rho^*}$ | 1 | $\frac{1}{\mu^*}$ | $\frac{1}{Ca}$ |

## Numerical Methods

- *Basilisk* will be used for the simulation.
- Incompressible solver `navier-stokes/centered.h`
- Multiphase nature given by `two-phase.h`

The projection method[1][2] is used to decouple the computations of pressure and velocity fields:

$$u_f^{n+1} \leftarrow u_f - \Delta t \alpha \nabla p \tag{7}$$

$$\nabla \cdot u_f^{n+1} = 0 \tag{8}$$

$$\nabla \cdot (\alpha \nabla p) = \frac{\nabla \cdot u_f}{\Delta t} \tag{9}$$

[1] Chorin et al.

## Numerical Methods

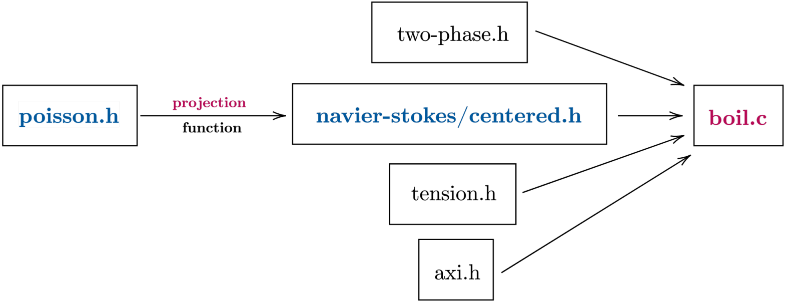
However, the projection method is based on a null divergence for velocity. In order to keep this method in accordance with the formulation made with the term source, it is necessary to adjust:

$$u_f^{n+1} \leftarrow u_f - \Delta t \alpha \nabla p \tag{10}$$

$$\nabla \cdot u_f^{n+1} = \mathbf{S}_v \tag{11}$$

$$\nabla \cdot (\alpha \nabla p) = \frac{\nabla \cdot u_f - \mathbf{S}_v}{\Delta t} \tag{12}$$

# Implementation Framework



## poisson.h

Implementation of the source term:

```
mgstats project (struct Project q)
{
  (...)
  scalar div[];
  foreach() {
    div[] = 0;
    foreach_dimension()
      div[] += uf.x[1] - uf.x[];
      div[] /= dt*Delta;
      div[] -= Sv[]/Delta;
  }
  (...)
}
```

# boil.c

Setup of physical variables:

```c
int main() {
  size (10);
  init_grid (1 << LEVEL);

  rho1 = 1.;
  rho2 = 1./RHOR;
  mu1 = 1.;
  mu2 = 1./MUR;
  f.sigma = 1./Ca;

  run();
}
```

We reformulate the dimensionless physical parameters.

- $\rho_1 = 1$
- $\rho_2 = \frac{1}{\rho^*}$
- $\mu_1 = 1$
- $\mu_2 = \frac{1}{\mu^*}$
- $\sigma = \frac{1}{Ca}$

## boil.c

Update of $S_v$ over time:

```
event boiling (t++) {
  foreach(){
    Sv[] = 3*(1-f[])/(R0 + t);
  }
}
```

Which is in accordance to equation (5):

$$S_v = \frac{3U_b}{(R_{b,0} + U_b t)}$$

## Simulations

Two simulations were proposed for testing the implementation and its results:

- **Axisymmetrical bubble growing in the center of a box**. Just to test if the source term is working correctly and the bubble is indeed growing.
- **Hemispherical axisymmetrical bubble growing attached to a wall**. Proposed to test the robustness by comparing it to recent works in microlayer formation.
- $(\rho^* = 100,\ \mu^* = 10,\ Ca = 0.1)$.

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    - Convergence Study
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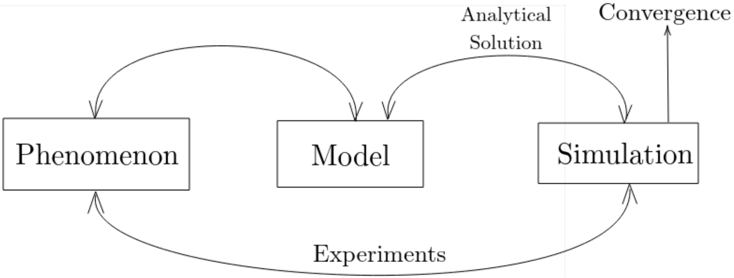
# Is the simulation correct?



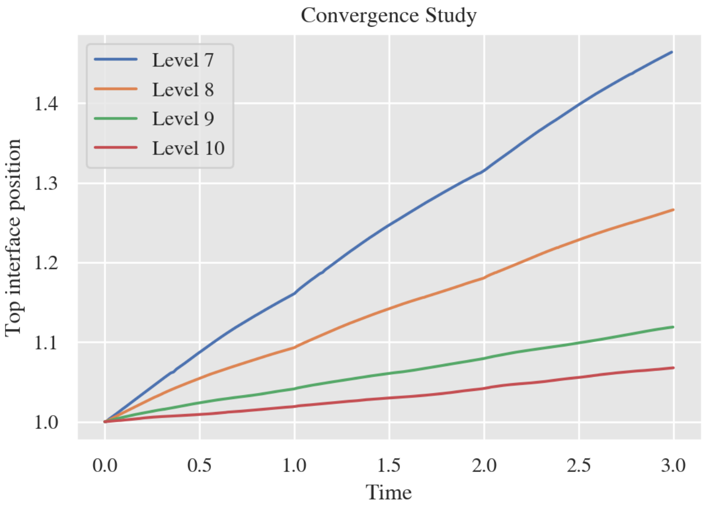
## Refinement

Throughout the simulation, many refinement choices can be made:

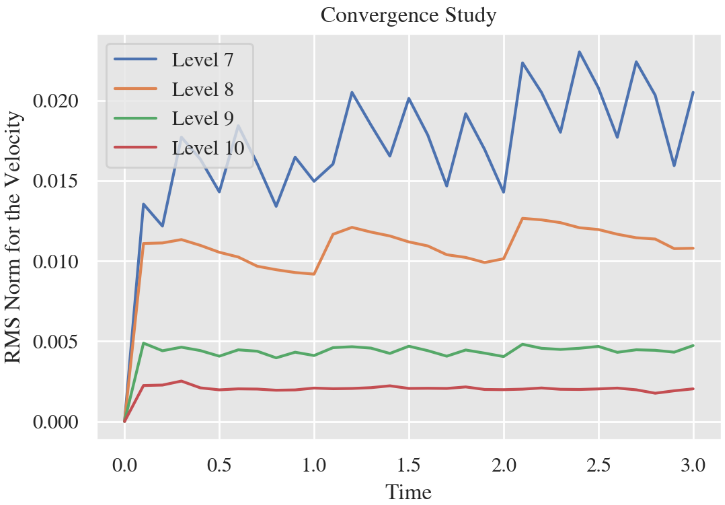
```
(...)
init_grid (1 << LEVEL);
(...)
refine (sq(x) + sq(y) - sq(R0*1.20) < 0
&& level < LEVEL);
(...)
event adapt (i++) {
  double uemax = 5e-3;
  adapt_wavelet ({f,u}, (double[]){0.01,uemax,
  uemax}, LEVEL, 5);
}
(...)
```

Therefore, different simulations were carried out by varying the LEVEL and collecting relevant data.

# Cap position with varying levels



# RMS of velocity with varying levels



# Conclusion

- The source term was successfully implemented, and the physics contributed by it as well.
- The implementation can be considered intrusive, as it directly edits the headers. Implementations that do not go outside the scope of the .c file will be considered.
- From a numerical perspective, the phenomenon of microlayer formation was weakly analyzed. An upcoming presentation will focus more on this aspect.

# Reference

[1] Alexandre Guion, Shahriar Afkhami, StÃľphane Zaleski, and Jacopo Buongiorno. Simulations of microlayer formation in nucleate boiling. *International Journal of Heat and Mass Transfer*, 127:1271–1284, 2018.

[2] Alexandre Joel Chorin. The numerical solution of the navier-stokes equations for an incompressible fluid. *Bulletin of the American Mathematical Society*, 73(6):928–931, 1967.

*Thanks!*

## Annexe

- $\mu_l$,$\mu_v$ : Liquid and vapor viscosities, resp.
- $\rho_l$,$\rho_v$ : Liquid and vapor densities, resp.
- $\sigma$ : Surface tension.
- $U_b$ : Bubble growth rate, the velocity at which the liquid vapor interface moves into the surrounding liquid.
- $\theta_{dx}$ : Microscopic contact angle at scale dx, between the liquid vapor interface and the wall, and at a given reference length scale dx.
- $r$ : Radial distance from bubble root.
- $t$ : Time
- $\delta$ : Unknown local thickness of the liquid microlayer forming at the wall.