# Development of a Multiphase Solver for Numerical Simulations of Thermally Driven Marangoni Flows

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## Motivation and Objectives

- **Development of a CFD solver** within the framework of the open source tool box OpenFOAM for the simulation of thermal Marangoni convection
- **Applications:** Crystal growth, metal welding, metal and organic alloys processing, droplet coalescence,...
- **Solver Validation:** simulation of the migration of droplets in a reduced gravity environment
- **Extend the capability** of the code to non-Newtonian viscoelastic liquids

## Methodology

- We use a semi-coupled Level-Set-VOF approach implemented into OpenFOAM
- The stresses at the interface are modelled by using a CSF (*Continuum Surface Force*) approach
- The energy transport equation is also solved: velocity and temperature fields are strongly coupled

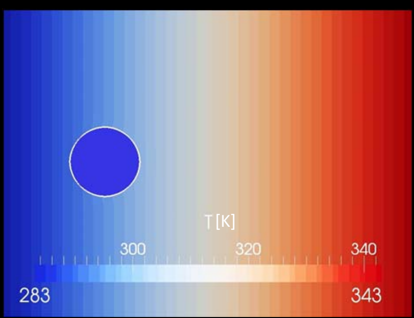
$$\rho_r\left(\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}\right)=-\nabla \mathbf{p}+\frac{1}{Re}\nabla\cdot\mu_r\left(\nabla\mathbf{u}+\nabla^T\mathbf{u}\right)+\frac{1}{Re\,\mathbf{Ca}}\left(\sigma^*(\mathbf{T})\mathbf{k}\delta\mathbf{n}+\nabla_{\|}\sigma^*(\mathbf{T})\delta\right)$$

$$\rho_r c_{p,r}\left(\frac{\partial \mathbf{T}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{T}\right)=\frac{1}{\mathbf{Ma}}\nabla\cdot\left(\mu_r\nabla\mathbf{T}\right)$$

$$\rho_r=\frac{\rho_{drop}}{\rho_{bulk}}\qquad \mu_r=\frac{\mu_{drop}}{\mu_{bulk}}\qquad c_{p,r}=\frac{c_{p\,drop}}{c_{p\,bulk}}$$

## Validation Problem

- Thermal Marangoni convection of a fluorinert droplet placed in a box filled with silicone oil in a reduced gravity environment
- A temperature gradient is imposed along the box



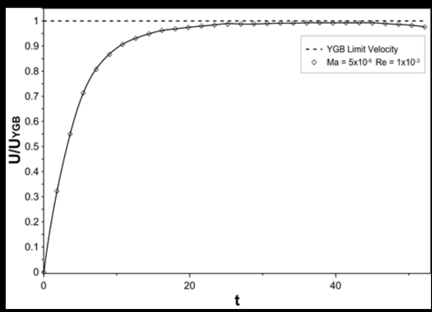

- Marangoni stresses caused by interfacial tension gradients along the interface cause the droplet to move from the cold side to the hot side
- The flow is governed by the following dimensionless parameters:

$$Re=\frac{\textit{Interfacial Stress Gradients}}{\textit{Viscous Stresses}}\qquad Pr=\frac{\textit{Kinematic Viscosity}}{\textit{Thermal Diffusivity}}$$

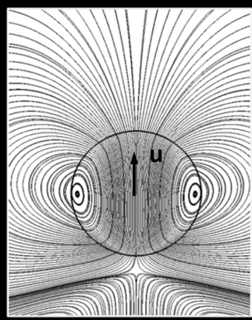
$$Ma=Re\,Pr=\frac{\textit{Thermal Convection Rate}}{\textit{Thermal Diffusion rate}}\qquad Ca=\frac{\textit{Viscous Forces}}{\textit{Interfacial Forces}}$$

- We performed a set of simulations by varying the Marangoni number "Ma" whilst the Prandtl and Capillary numbers have been kept constant

## Droplet migration at vanishing Marangoni and Reynolds numbers

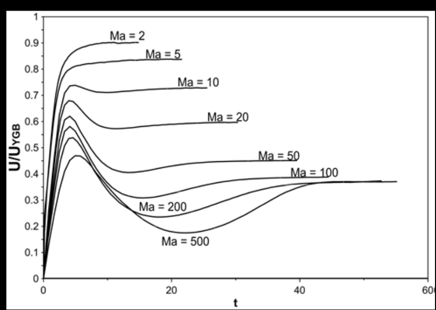



Droplet velocity: comparison between the analytical solution and simulation

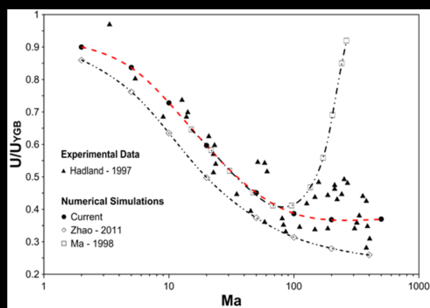



Streamlines

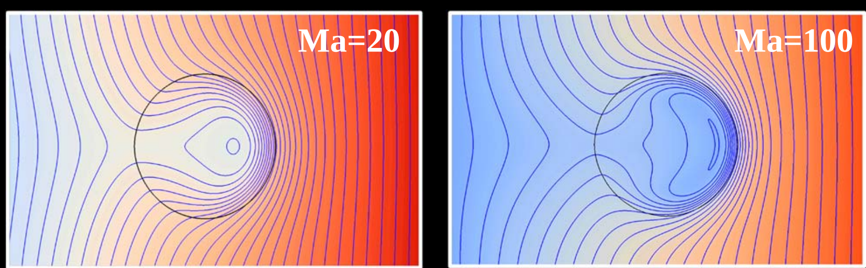
## Effect of Marangoni number on droplet migration under reduced gravity conditions




Numerical Results: Normalized Droplet velocity as a function of Ma




Asymptotic droplet velocity: comparison between experiments and simulations




Temperature distribution in proximity to the droplet

## Conclusions and Future Work

- The Solver has been tested for a wide range of Marangoni numbers
- In the case of vanishing Marangoni and Reynolds number we successfully matched the analytic solution of Young with an error < 1%
- Our predictions are in excellent agreement with the experimental measurements of Hadland [1]
- Next, we aim to investigate the effect of the shear dependent viscosity and elasticity on the thermocapillary motion of droplet

[1] P. H Hadland, R. Balasubramanian, G. Wozniac, R. S. Subramanian, *"Thermocapillary Migration of bubbles and drops at moderate to large Reynolds Numbers in Reduced Gravity"*, Exp. Fluids, 26, 240 (1999)

[2] J. Zhao, L. Zhang, Z. Li, W. Qin, *"Topological Structure evolvement of Flow and Temperature in deformable drop Marangoni Migration in Microgravity"*, Journal of Heat and Mass Transfer, 54 (2011)