TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG
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SFB 920

Multifunktionale Filter für die Metallschmelzefiltration –
ein Beitrag zu Zero Defect Materials

Application of the discrete phase model in metallurgical processes

Amjad Asad, Christoph Kratzsch, Rüdiger Schwarze

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Outline

- Motivation
- Discrete phase model
- Model validation
- Application in metallurgy
- Outlook

Motivation

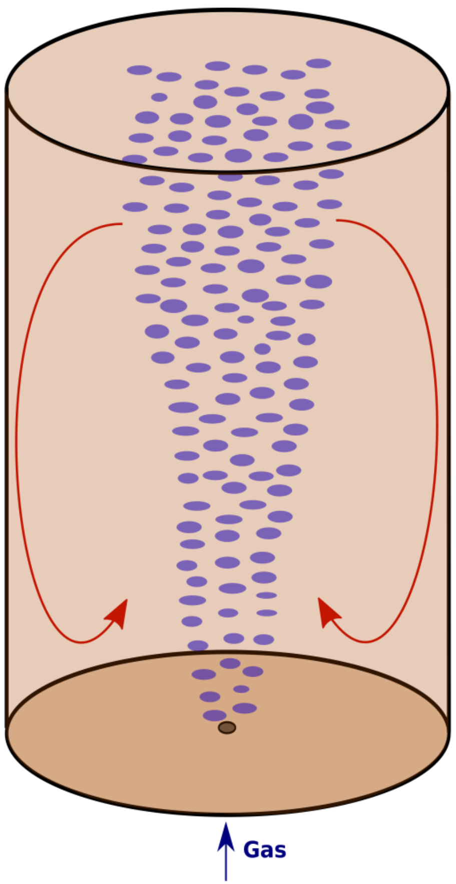
a) Multi-phase flow of interest in metallurgical processes

b) Bubbles/particles/slag/melt

c) Considerable impact on flow pattern

d) Detaild knowledge of interplay between phases to enhance steel quality

e) Magnetic field used to control the melt flow



Discrete phase model (DPM)

a) Liquid as continuum

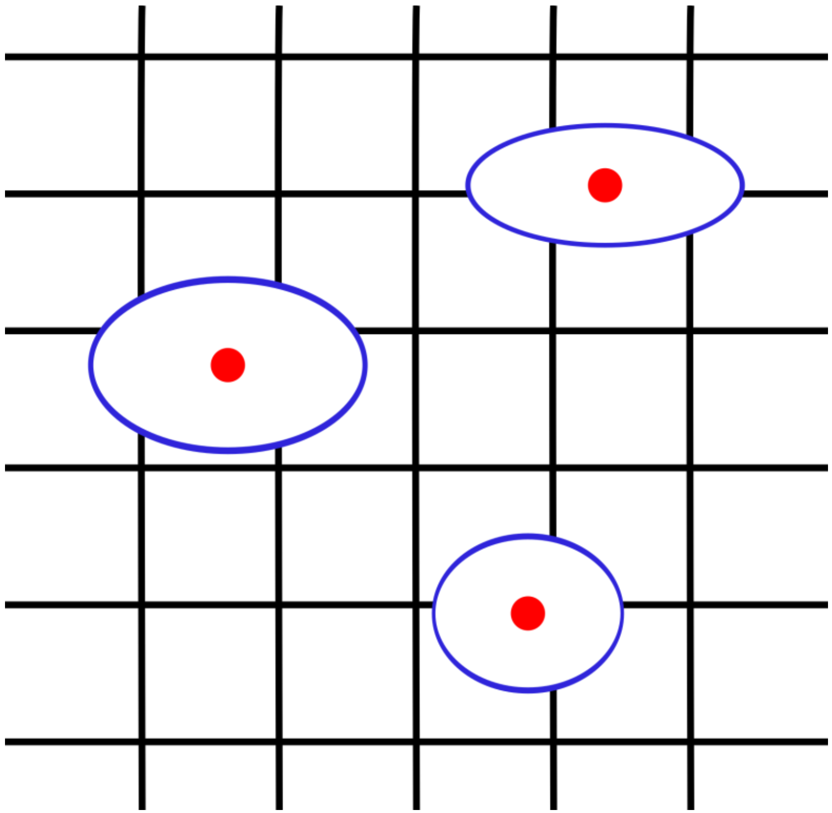
b) Disperse phase in Lagrangian-way

c) Disperse phase as mass point

d) Bubbles or soild particles

e) Without transient shape deformation

f) Two-way coupling



Discrete phase model (DPM)

Equations in OpenFoam

Navier-Stokes-Equation- NSG

$$\varrho \frac{\partial \underline{\bar{u}}}{\partial t} + \varrho \underline{\bar{u}} \cdot \nabla \underline{\bar{u}} = -\nabla \bar{p} + \eta \Delta \underline{\bar{u}} + \underline{\bar{f}}_W + \underline{\bar{f}}_L - \nabla \cdot \underline{\underline{\tau}}^{\mathrm{RS}}$$

$$\nabla \cdot \underline{\bar{u}} = 0$$

Two-way coupling

One-way coupling

Euler-Lagrange - EL

$$m_p \frac{d\underline{u}_p}{dt} = \underline{F}_{\mathrm{B}} + \underline{F}_{\mathrm{D}} + \underline{F}_{\mathrm{VM}} + \underline{F}_{\mathrm{lift}} + \underline{F}_{\mathrm{G}} + \underline{F}_{\mathrm{press}}$$

Volume of Fluid - VOF

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\underline{u}\alpha) + \nabla \cdot (u_r \alpha (1-\alpha)) = 0$$

MHD

$$\underline{\bar{f}}_L = \underline{\bar{j}} \times \underline{B}_0$$

$$\underline{\bar{j}} = \sigma \left(-\nabla \bar{\psi} + \underline{\bar{u}} \times \underline{B}_0 \right)$$

$$\nabla^2 \bar{\psi} = \nabla \cdot (\underline{\bar{u}} \times \underline{B}_0)$$

Turbulence:
LES/RANS or URANS

Model Validation

Bubble column

a) Experiment by Deen et al. [1]

b) Water/air bubbles

c) Sparger with 47 holes

d) 3200 bubbles/second

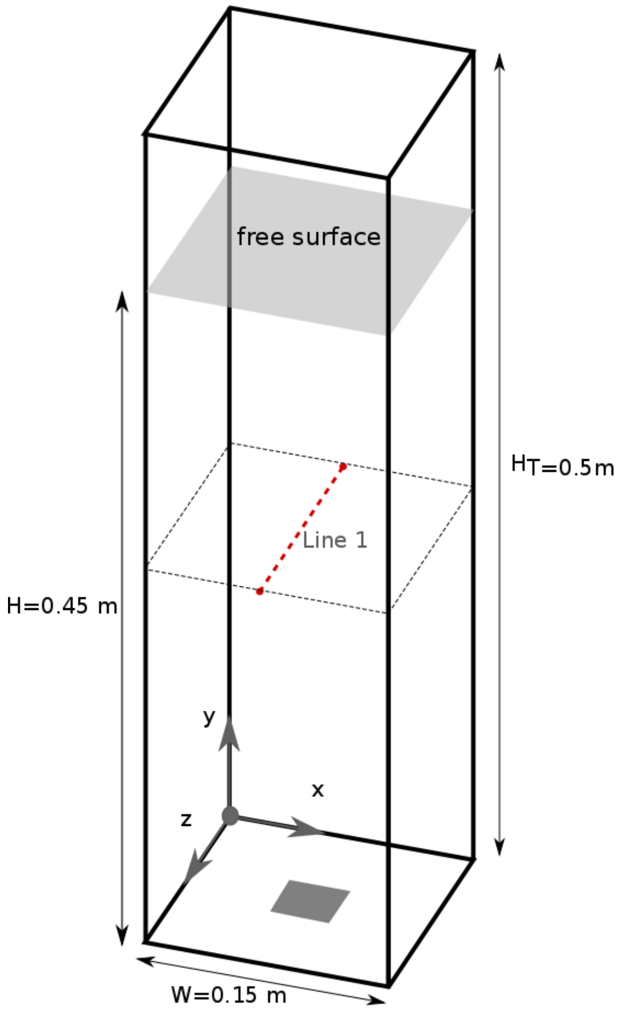
e) Bubble diameter 4 mm

f) VOF to capture free surface

g) DDES model

h) Forces: $\underline{F}_G, \underline{F}_B, \underline{F}_D, \underline{F}_{VM}, \underline{F}_L, \underline{F}_p$

i) Comparison between drag models



Model Validation

Drag coefficient

a) Tomiyama drag model [2]

$$CD = max\left\{min\left[\frac{16}{Re_b}\left(1+0.15Re_b^{0.687}\right),\frac{48}{Re_b}\right],\frac{8}{3}\frac{Eo}{Eo+4}\right\}$$

b) Ishii and Zuber [3]

$$CD = \max\left\{\frac{24}{Re_b}\left(1+0.15Re_b^{0.687}\right),\min\left[\frac{4}{3}\sqrt{2Eo},\frac{8}{3}\right]\right\}$$

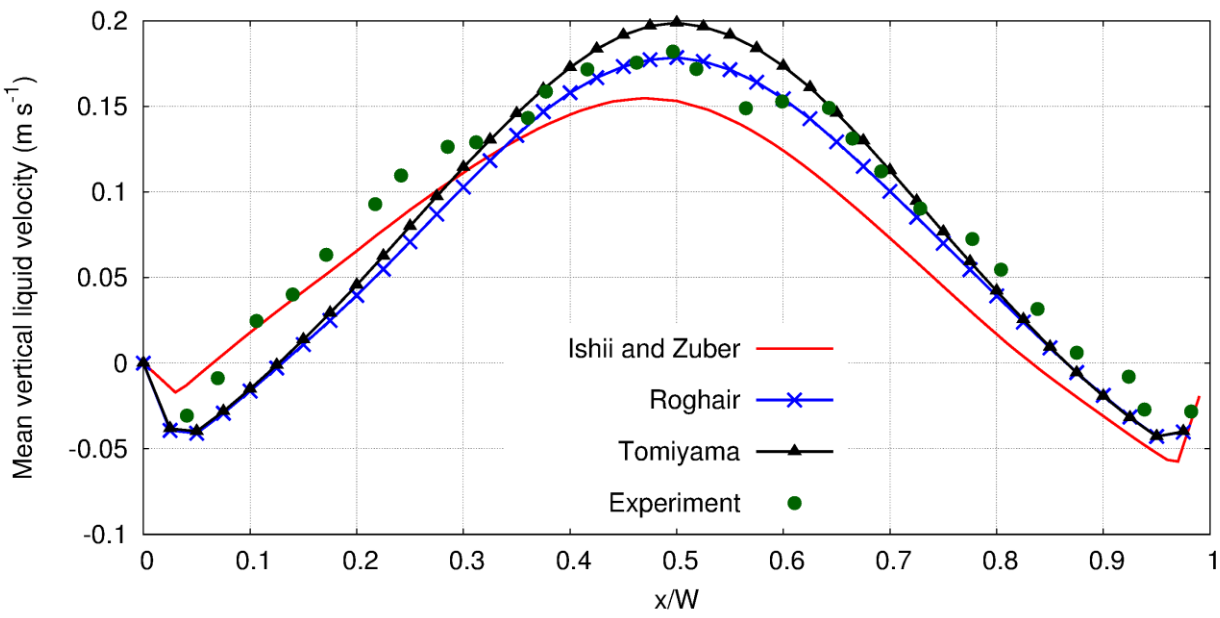
c) Roghair drag model [4]

$$\frac{CD}{CD_\infty(1-\alpha_{loc})} = f(Eo,\alpha_{loc}) = 1+\left(\frac{18}{Eo}\right)\alpha_{loc}$$

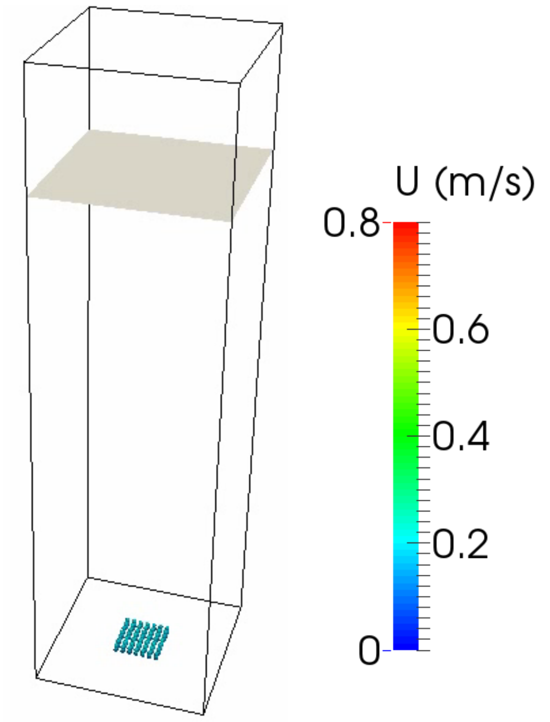
$$CD_\infty = \sqrt{Cd(Re_b)^2 + Cd(Eo)^2}$$

Model Validation

Results



Vertical velocity of liquid



3d View

Conclusion

a) Drag model impact on results quality

b) Good agreement compared to experiment

c) Bubble induced turbulence model

d) Optimize condtions at inlet

e) Change of bubble diameter

Ladle flow

a) Enhancement of steel homogeneity

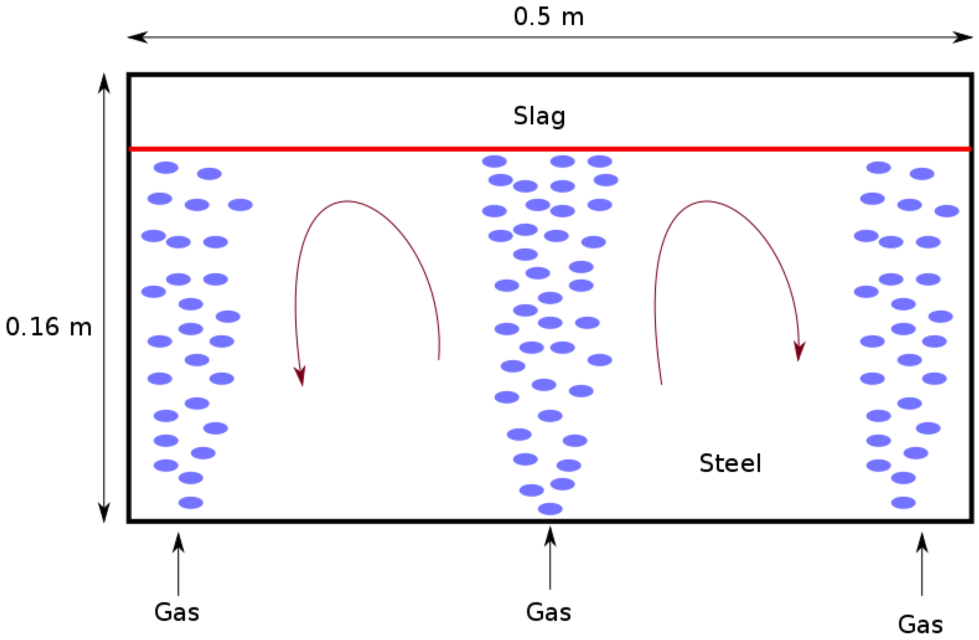
b) DDES model

c) Three inlets at the bottom

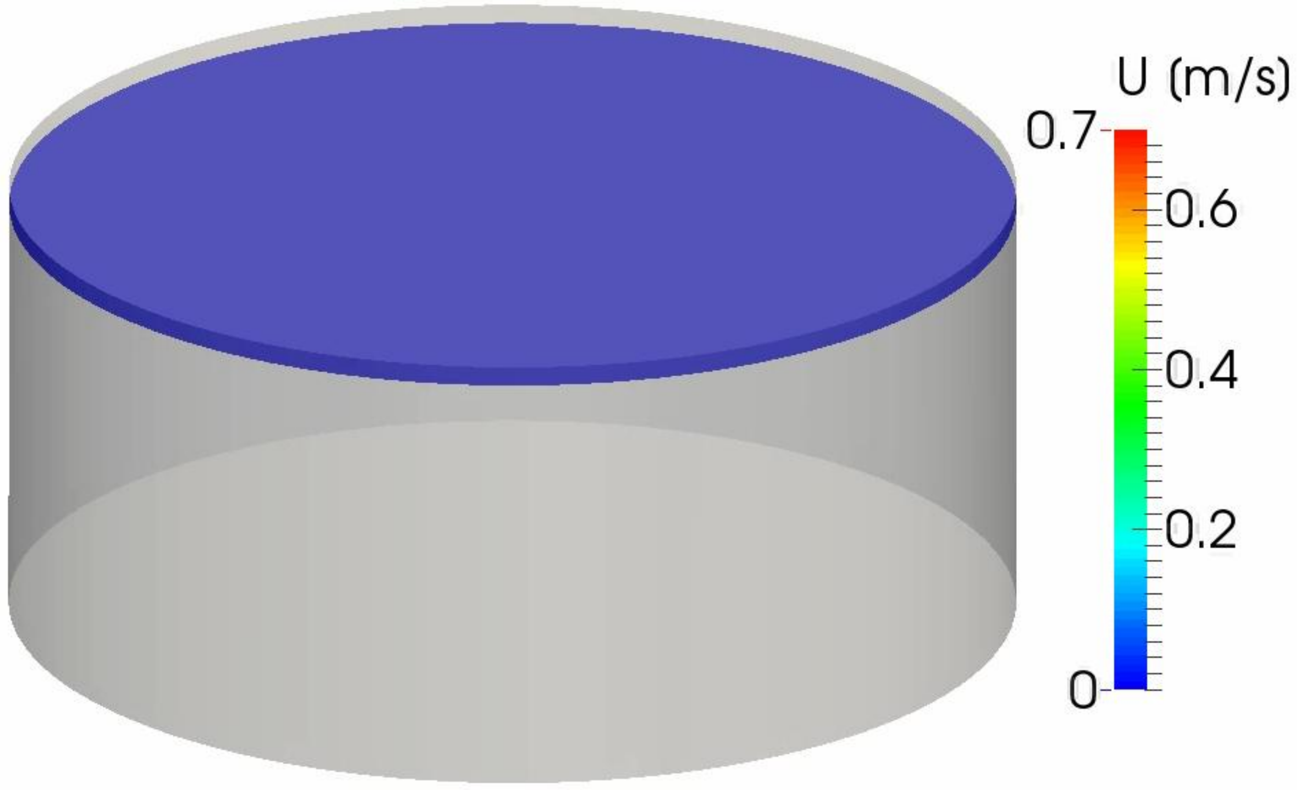
d) 490 bubbles/second

e) Bubble diamater 4 mm

f) Slag behavior captured by VOF



Ladle flow



Bubbly flow under magnetic field

a) Argon bubbles/ melt

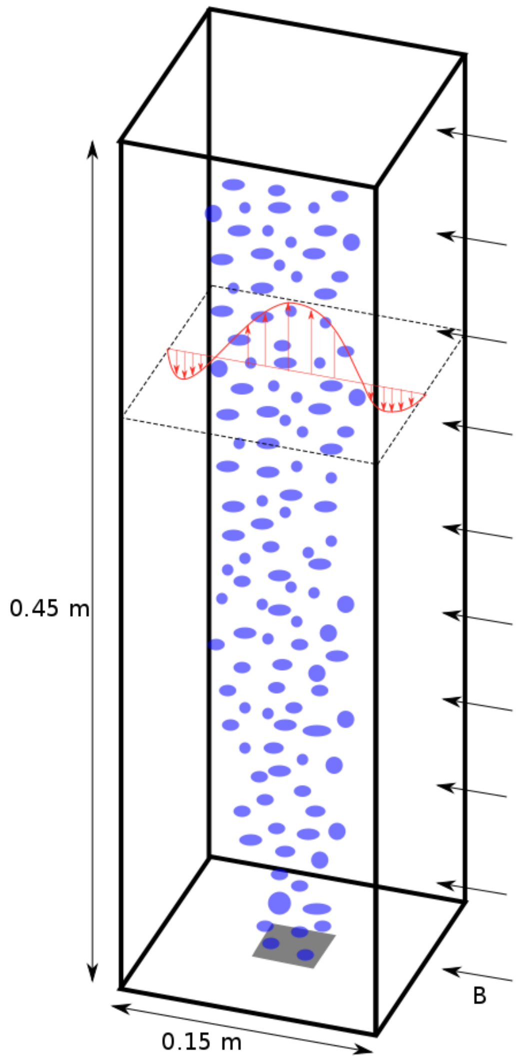
b) 2300 bubbles/second

c) Bubble diameter 4 m

d) Bubbles isolated

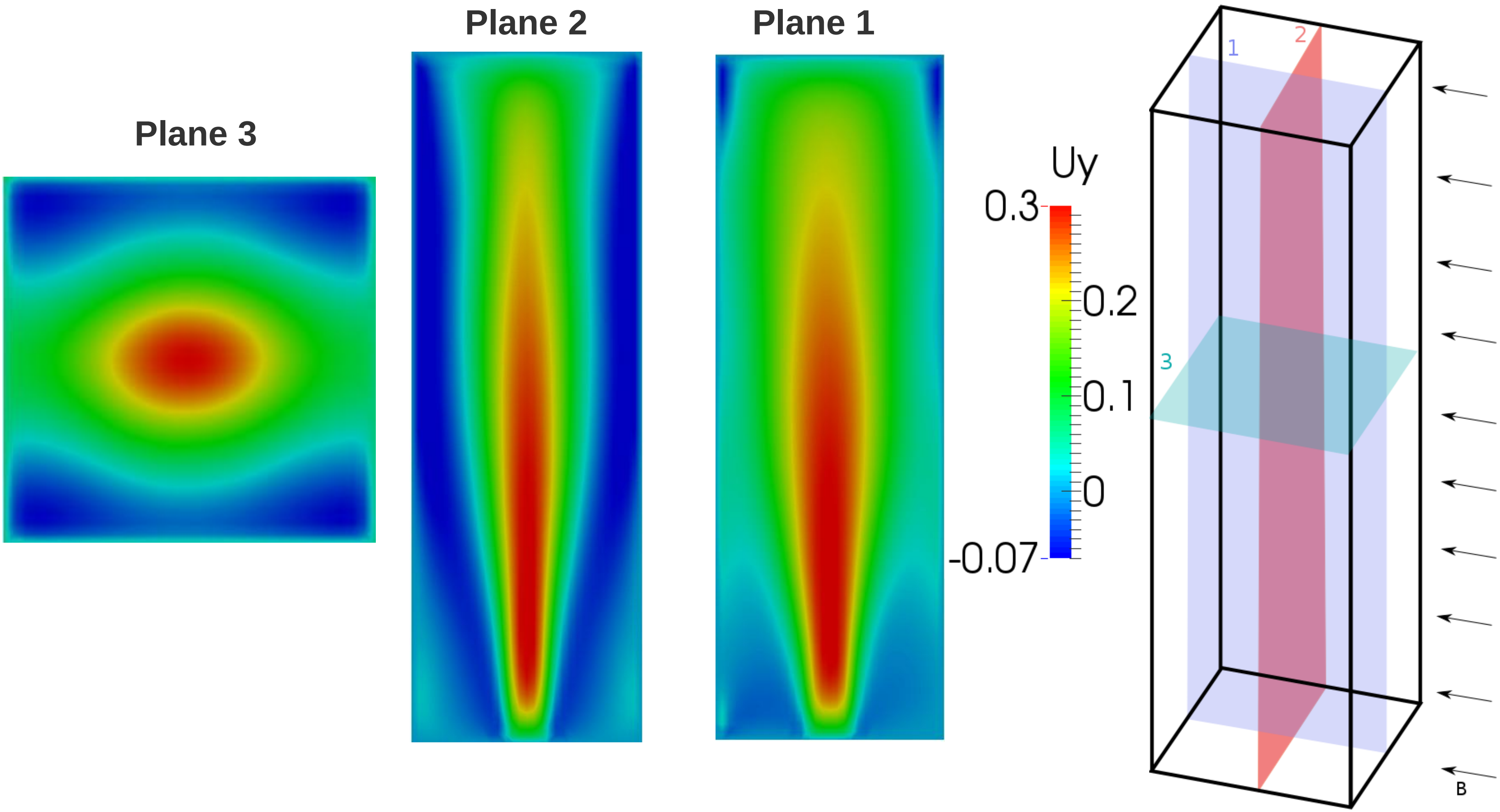
e) DDES model

f) $\underline{F}_{lorentz}$ = J ^ B



Bubbly flow under magnetic field

Mean vertical velocity profile of liquid metal for B=0.05 T



Induction crucible furnance

a) Alternating magnetic field

b) Skin effect

c) High frequency

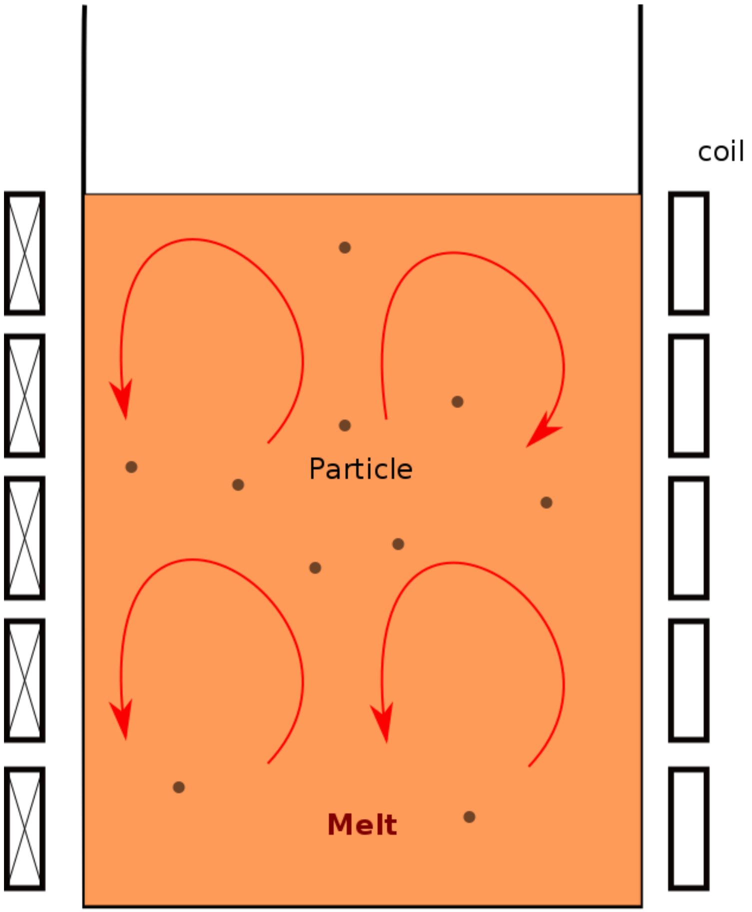
d) Lorentz force constant

e) Magnetic field by MaxFEM

f) Lorentz force interpolated

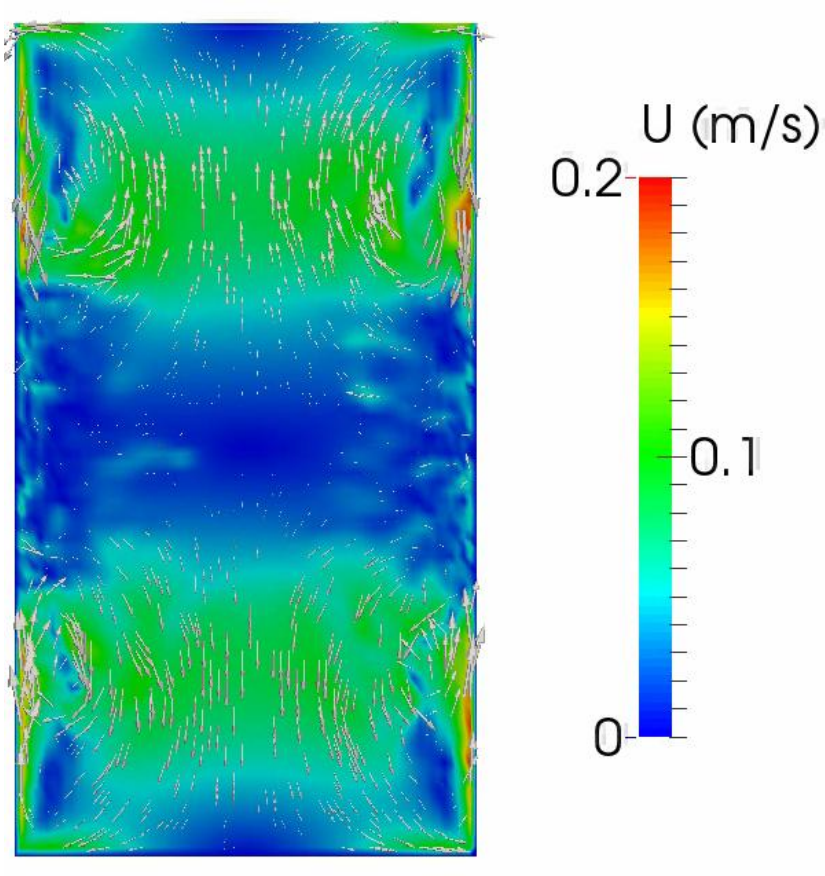
g) Flow driven by Lorentz force

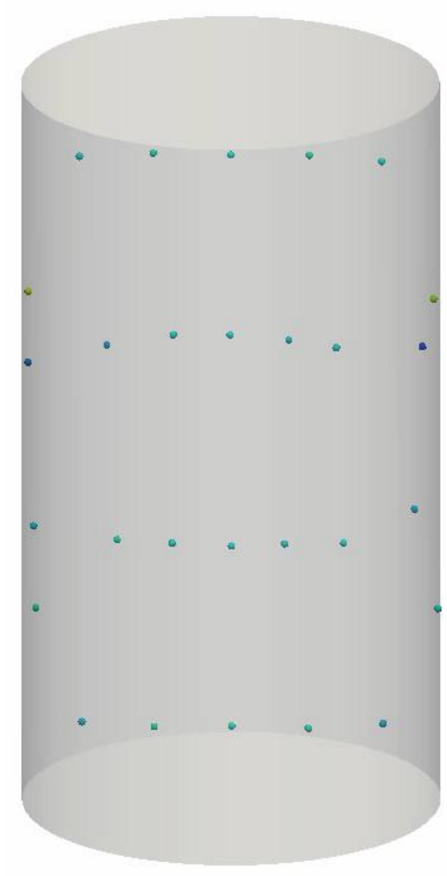
h) Solid particles in steelmaking



Induction crucible furnance

Slip wall





Flow field

Particles motion

Mold flow with particles and bubbles

a) 4 different phases

b) Solid particles and bubbles at mold inlet

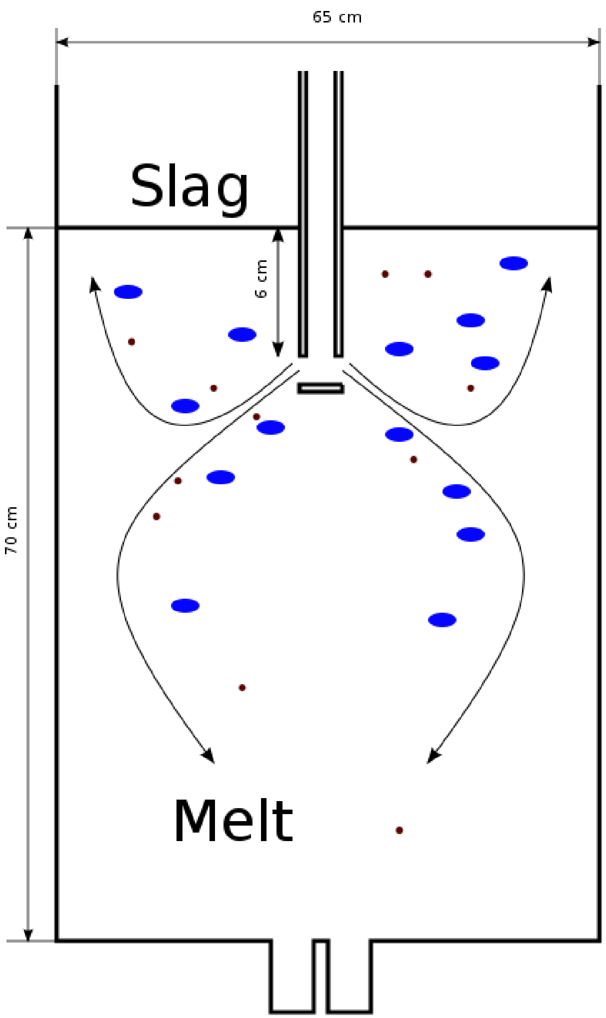
c) Solid particle diameter 20 µm

d) Bubble diameter 3 mm

e) Particle density 2000 kg/m^3

f) 30 particles/second

g) 60 bubbles/second

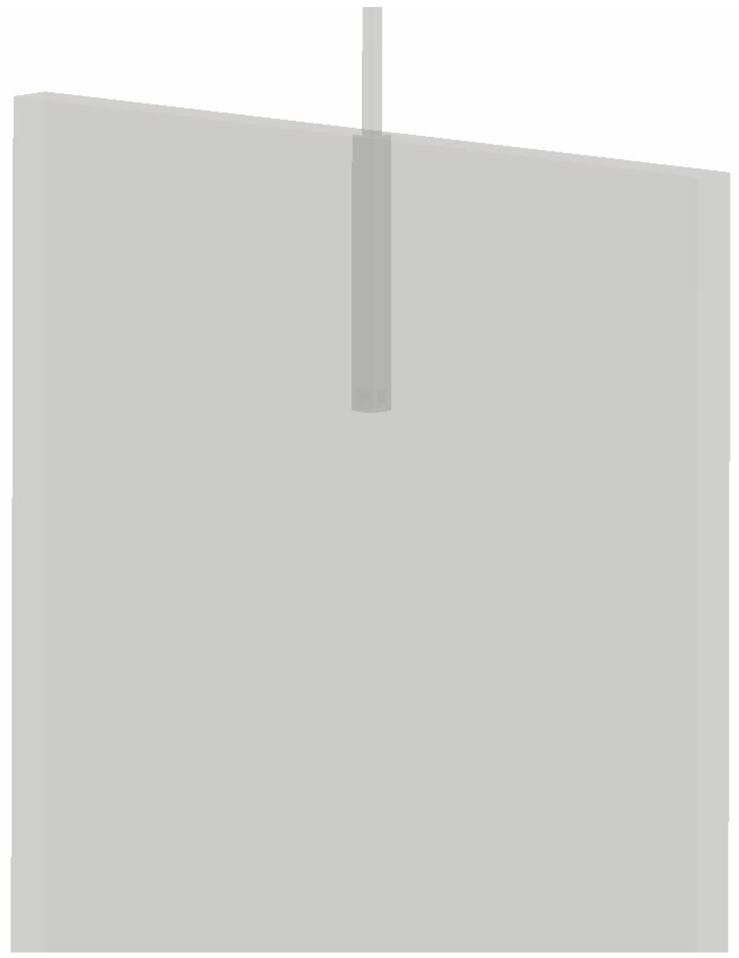


Mold flow with particles and bubbles

a) Solid particles: blue

b) Bubbles: red

c) Jet:iso-surface U=0.5



Bubble – particle attachment

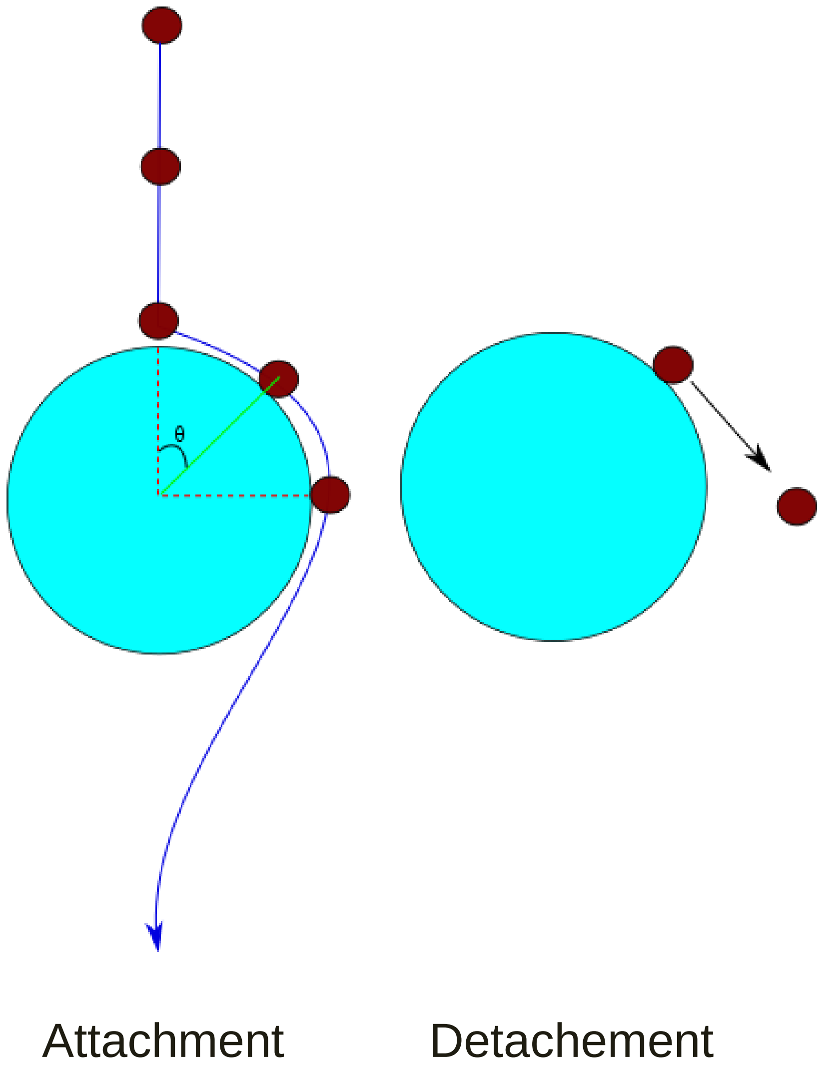
a) Particle attaches to bubble

b) Sliding time longer induction time

c) Velocity, contact angle, area

d) Detachement

e) Collision, turbulence



Bubble – particle attachment

Test case

a) Particle diameter 20 µm

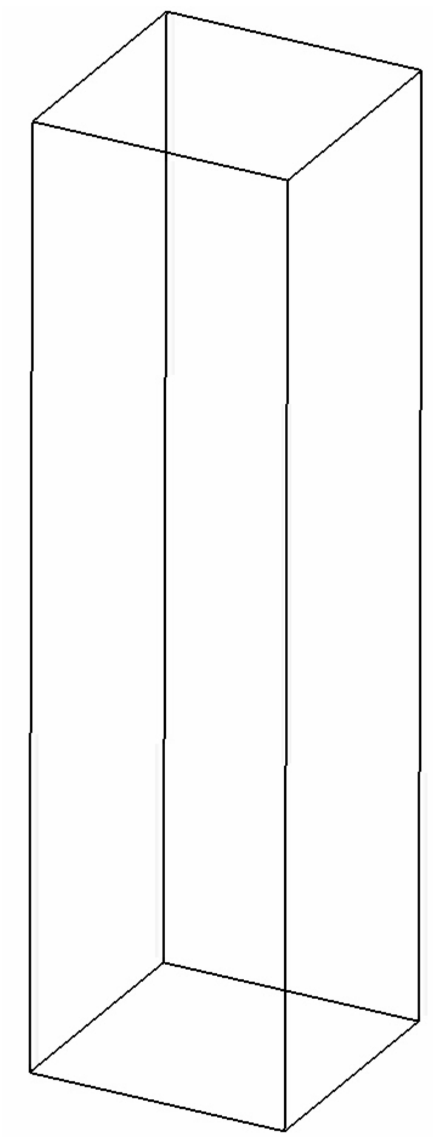
b) Bubble diameter 4 mm

c) Simple model

d) Particles deleted from domain

e) Detachement not considered

f) Model must be developed



Outlook

- Discrete phase model in OpenFOAM formulated
- Model validation by means of bubble column experiment
- Ladle flow
- Bubbly flow under effect of magnetic field
- Induction crucible furnance
- Mold flow with particles and bubbles
- Bubble- particle attachment

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Thanks for your Attention

References

[1] N. Deen, B. Hjertager, T. Solberg, In Proceedings of the 10th int. symposium on applied of laser techniques to fluid mechanics, Lisbon (Portugal) **2001**.

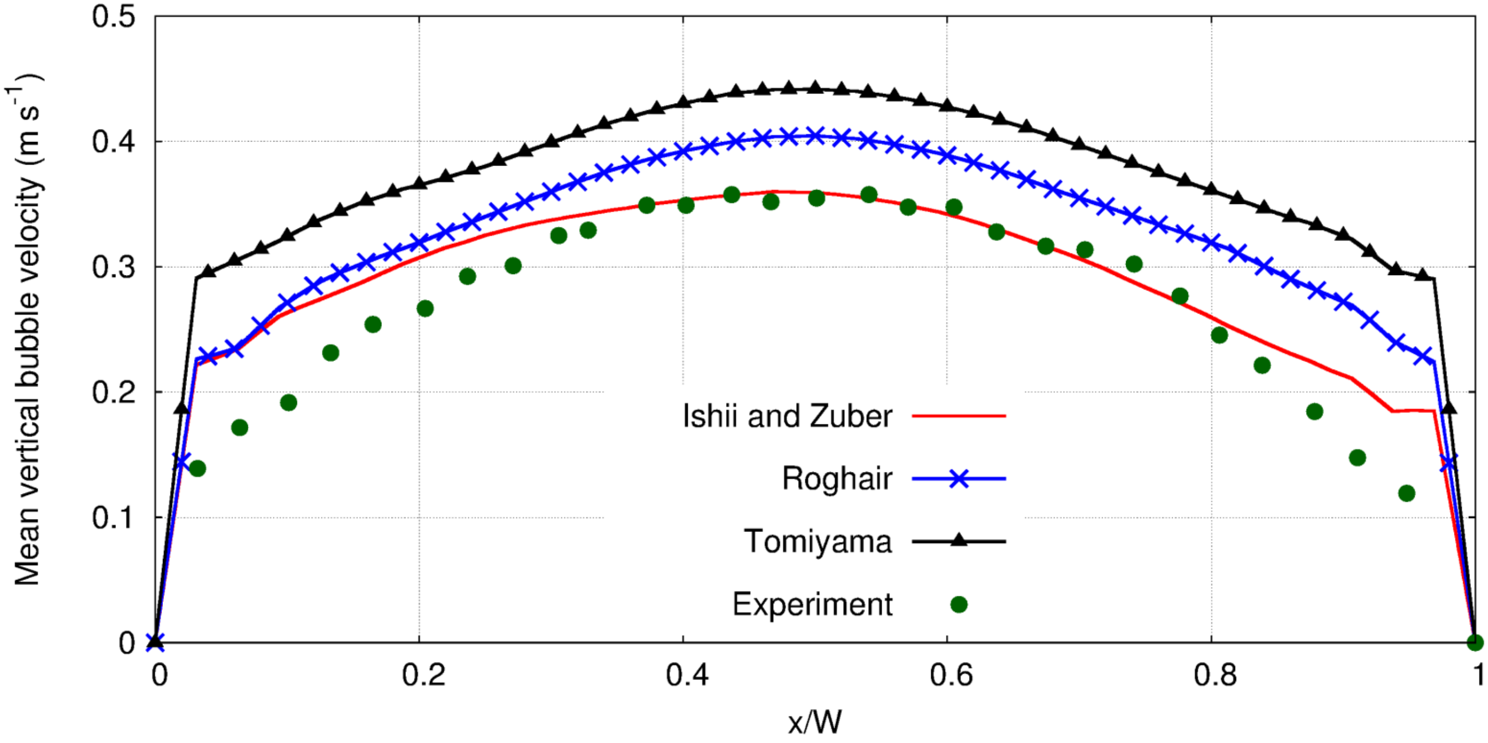
[2] Tomiyama, I. Kataoka, I. Zun, T. Sakaguchi, . JSME I. J. Series B **1998**, 41,472.

[3] M. Ishii, N. Zuber, *AIChE Journal* ***1979***, *25*, 843.

[4] I. Roghair, Y. Lau, N. Deen, H.M. Slagter, M. Baltussen, M. Annaland, M. V. S., J. Kuipers. *Chem. Eng. Sci.* **2011**, 66, 3204

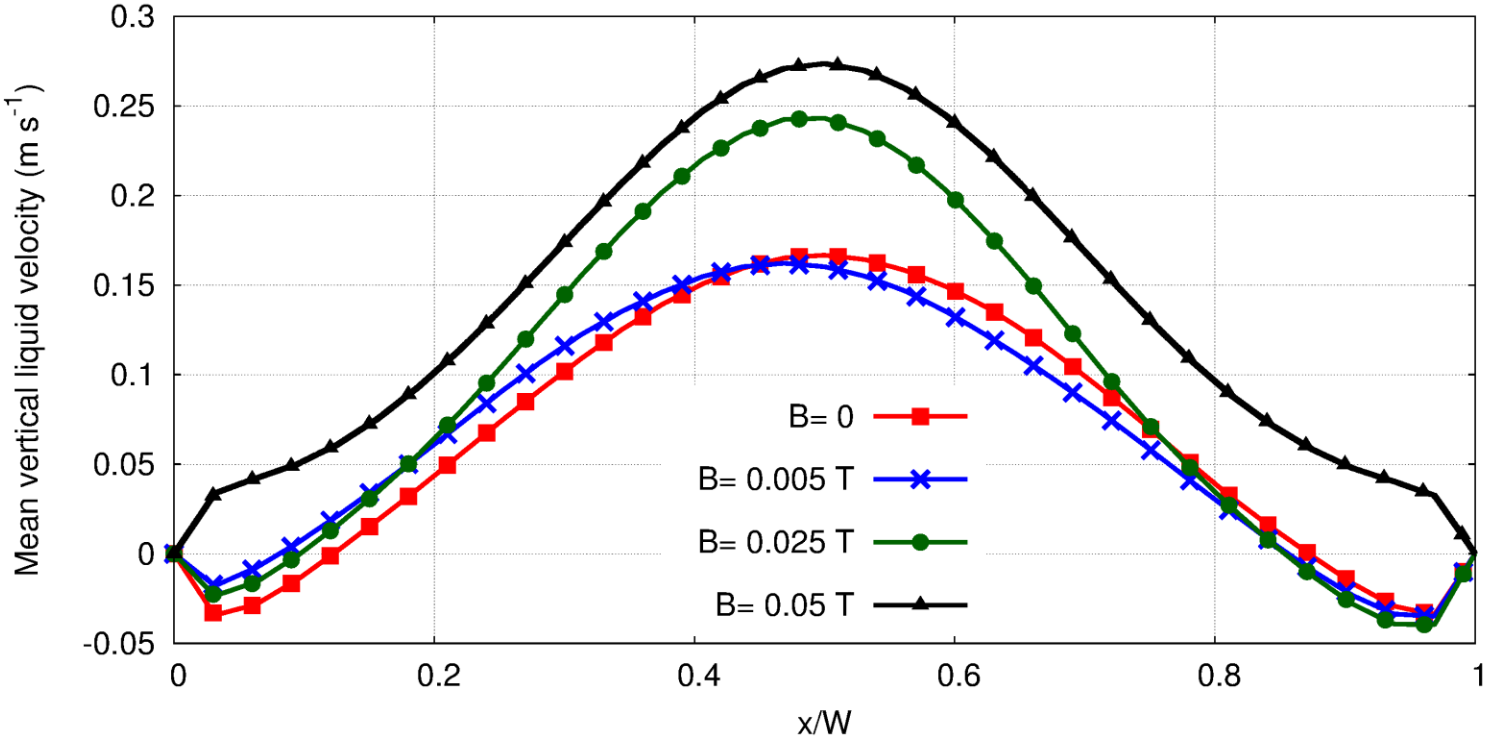
Model Validation

Mean vertical bubble velocity at a height of 252 mm

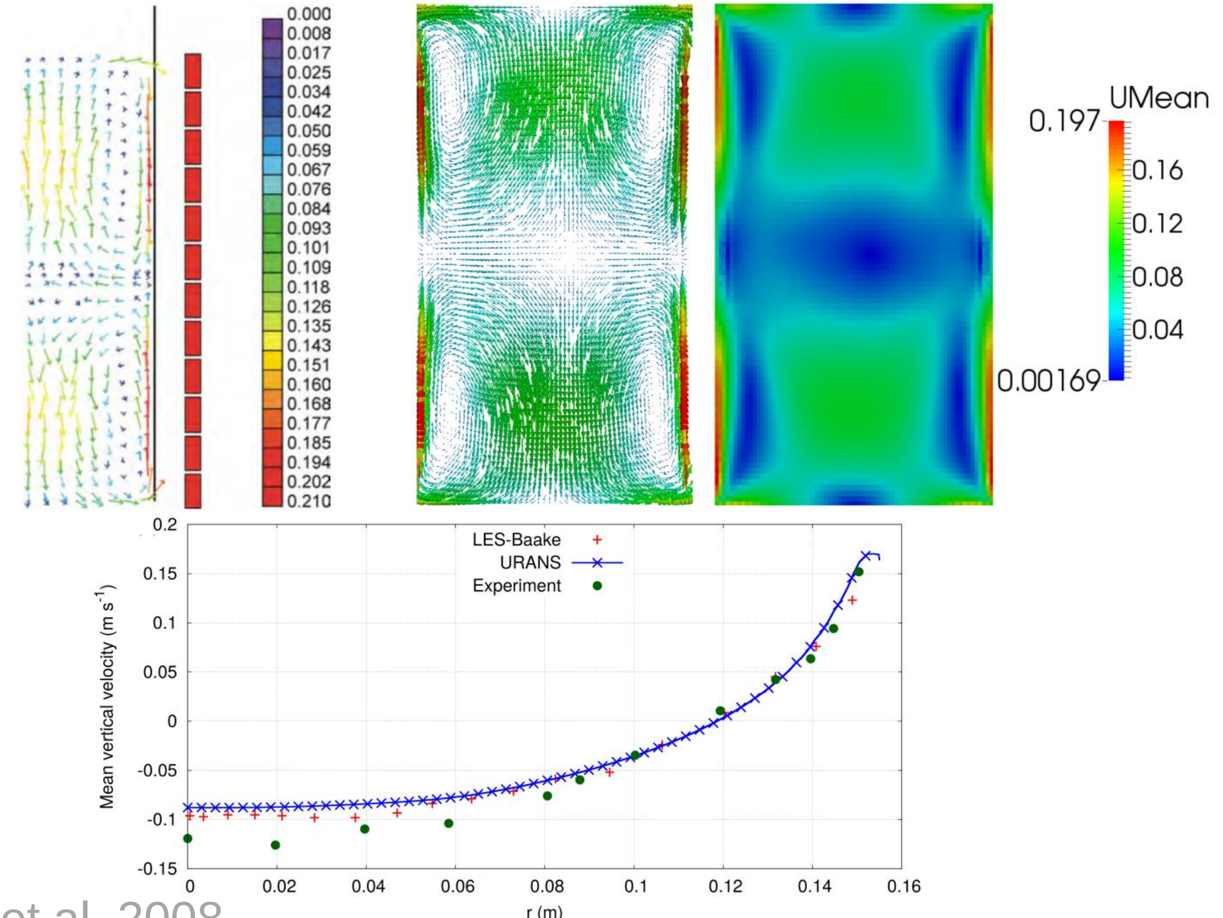


Bubbly flow under magnetic field

Mean vertical velocity of liquid at a height of 252 mm



Induction crucible furnance



Kirpo et al. 2008