# Multiphase Flow in Continuous Casting

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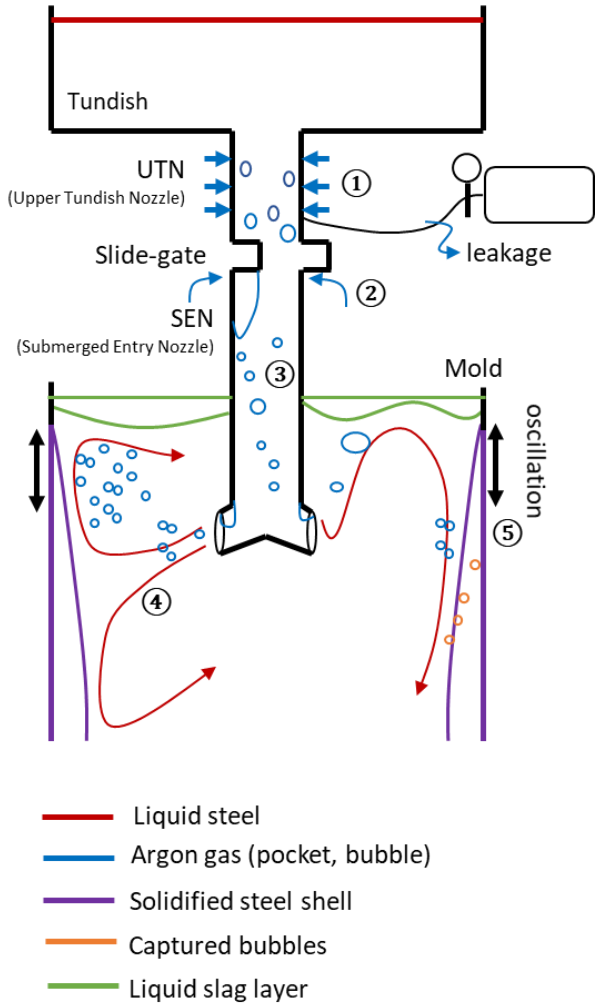
# Background

# Background of multiphase flow in CC




- Continuous Casting is a **multiphase process** due to **solidification / melting** and **argon gas injection**.
- **Argon gas injection** is beneficial for
  - Alleviating **air aspiration**
  - mitigating **nozzle clogging**
  - removing **impurities**
- Makes the system **multiphase (gas-liquid) turbulent flow.**
- Multiphase flow issues in CC:

  ① **Active** gas injection (stopper tip, UTN porous wall)
  ② **Passive** gas injection (aspiration)
  ③ Bubble interactions, **flow regime** and **size distribution**
  ④ **Fluid flow** in the mold
  ⑤ **Bubble capture** on the shell

- **How much gas** is in the system? (①+ ②)
- How is the gas **redistributed** into bubbles? (③)
- How does the **bubble size distribution** affect the CC process (④+ ⑤)

# Question

Q. Have you **experienced** or **studied** any of issues related to **multiphase flow?:**

a) **Argon flow rate control** → mold level fluctuations, deep oscillation marks

b) **Aspiration/oxidation** → clogging & non-metallic inclusions

c) **Bubble entrapment** → pinholes

d) **Slag-metal interface instability** → slag entrapment, inclusions, slivers

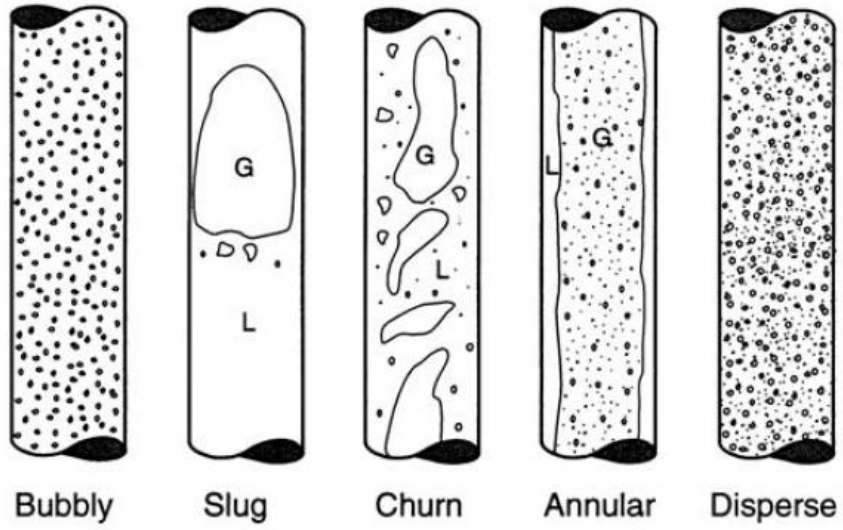
- **Possible** to **model** these phenomena?

# Theory

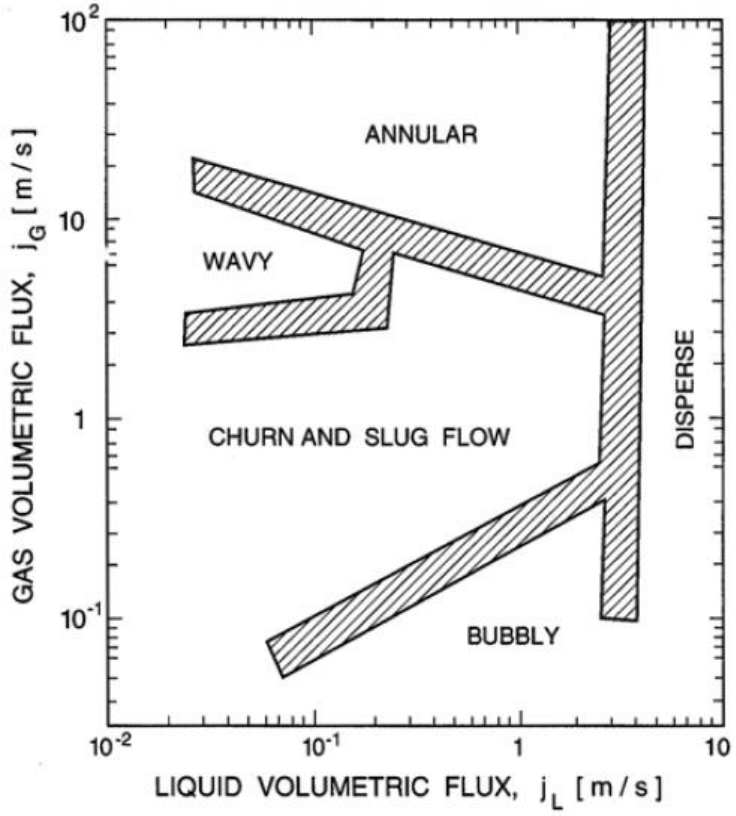
# Complexity of multphase flow

- **Modeling** of **steel-argon** multiphase **flow** is **challenging**:
  - **Absence** of **reliable model**
  - Different behavior depending on **flow regime**
  - **Difficulties in measurement**

- How would the **flow regime map** look like **for steel-argon**?




Flow regime map for **water-air upflow** in vertical pipe (**d=2.5cm**)




**Weisman (1983), Two-phase flow patterns**

# Classification of multiphase flow models

From Yang, Vanka and Thomas, ISIJ (2019)

## Field-based models (Eulerian approach)

Interface is blurry

**Quasi – multiphase models**

Algebraic-Slip Mixture model, Modified Mixture model

↕ Another set of governing equations for gas

**Multi-fluid models**

**Eulerian-Eulerian model (EE)**, Interfacial Area Concentration model
Homogeneous MUSIG model, Inhomogeneous MUSIG model

Interface is sharp

**Interface tracking methods**

**Volume Of Fluid model (VOF)**, Level Set method (LS)
Front Tracking method (FT)

↕ Mesh is adapted based on interface

**Moving Grid methods**

Arbitrary Lagrangian-Eulerian methods, Spines model

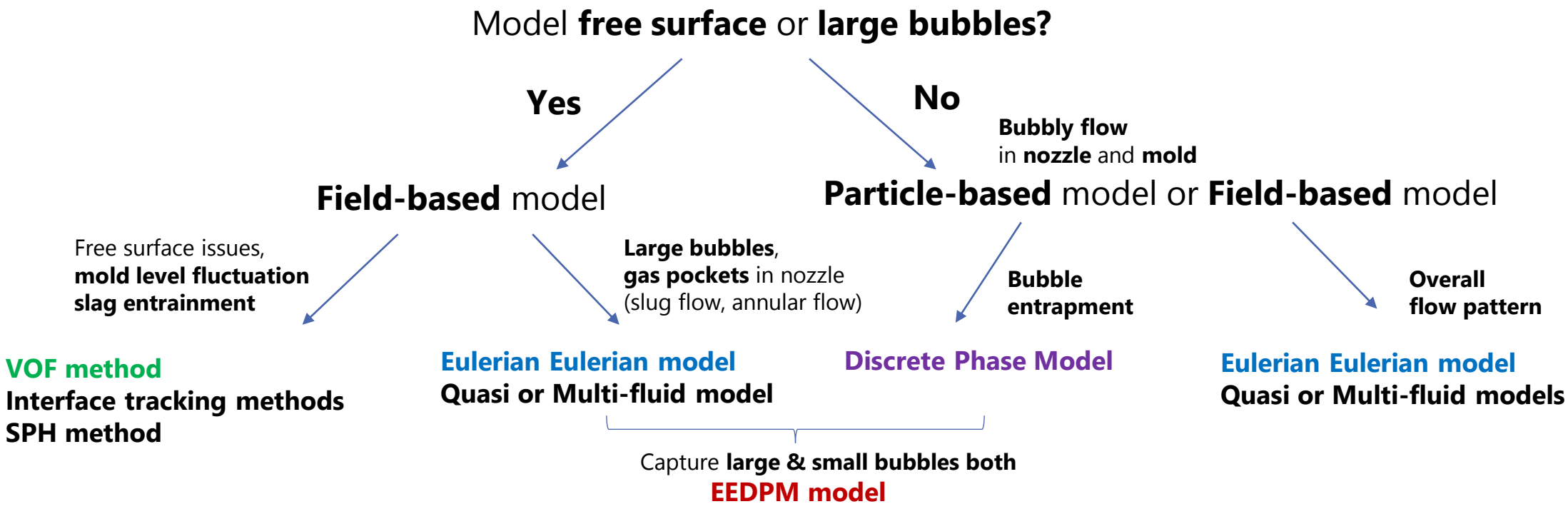
## Particle-based models (Lagrangian approach)

| | Liquid | Gas |
|---|---|---|
| **Macro-scale** | **continuum (grid-based)** | **particle (no grid)** |
| **Discrete Phase Model (DPM)** | | |
| Smoothed Particle Hydrodynamics (SPH) | particle (no grid) | particle (no grid) |
| **Meso-scale** | | |
| Lattice Boltzmann Method (LBM) | particle (grid-based) | particle (grid-based) |
| Dissapated Particle Dynamics (DPD) | particle (no grid) | particle (no grid) |
| **Micro-scale** | | |
| Molecular Dynamics | particle (no grid) | particle (no grid) |

**Mesh (grid) based** ↔ **Meshless**

# Selection of multiphase flow model

- **Criteria** for the selection:
  - **What phenomena** you want to model?
  - What **flow regime** are you targetting?
  - Available **computational power**?

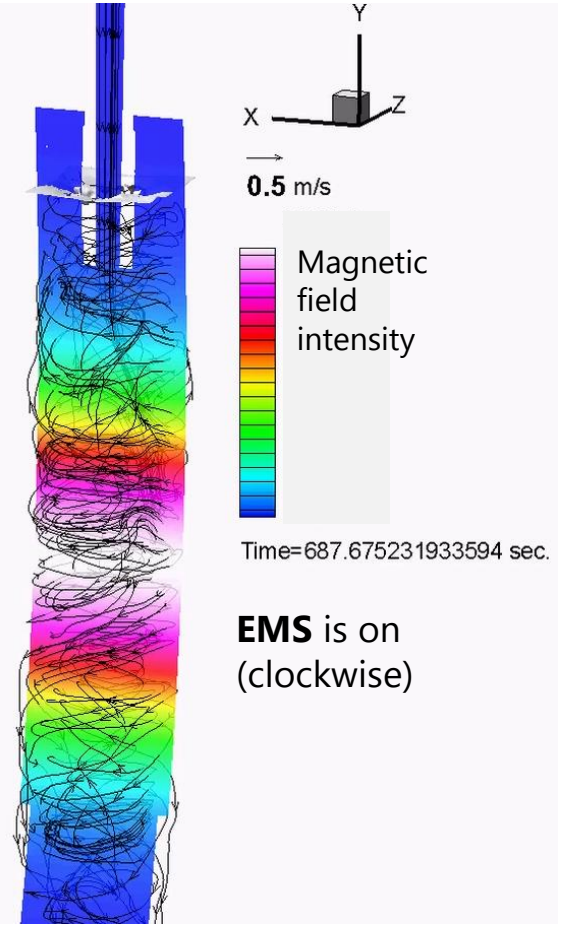


# Examples

# Example 1. Slag entrapment in billets

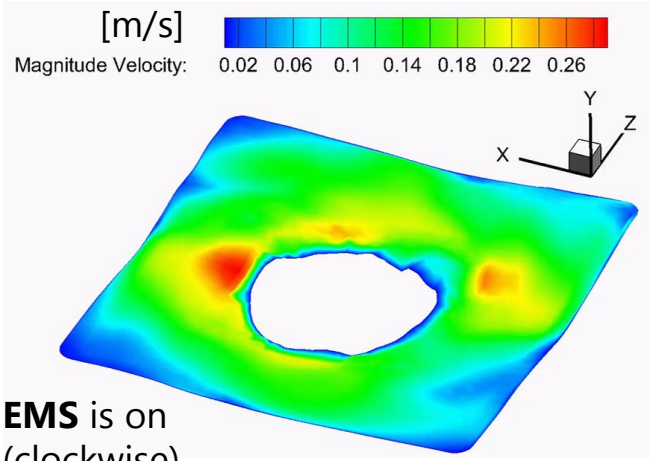
- **VOF** for capturing the **metal level instability** and **slag entrainment**

**Streamlines of liquid steel and magnetic field density**



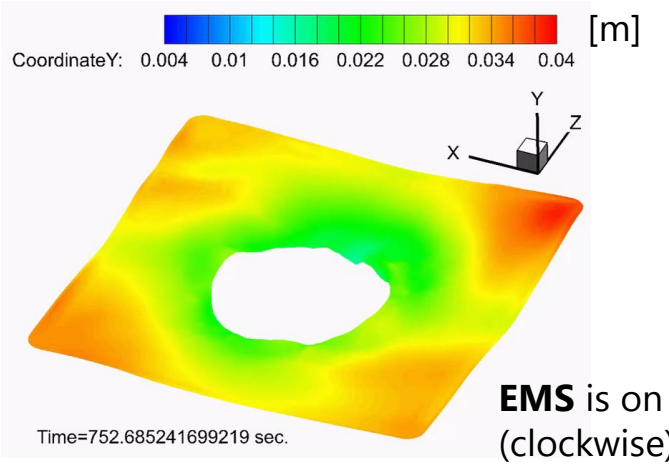

**EMS** is on (clockwise)

**Velocity magnitude of metal level**



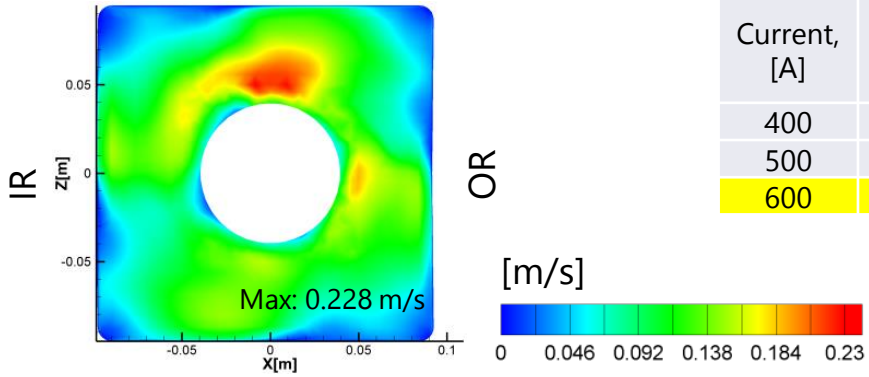

**EMS** is on (clockwise)

**Height contour of metal level**




**EMS** is on (clockwise)

**Time-averaged interface velocity**



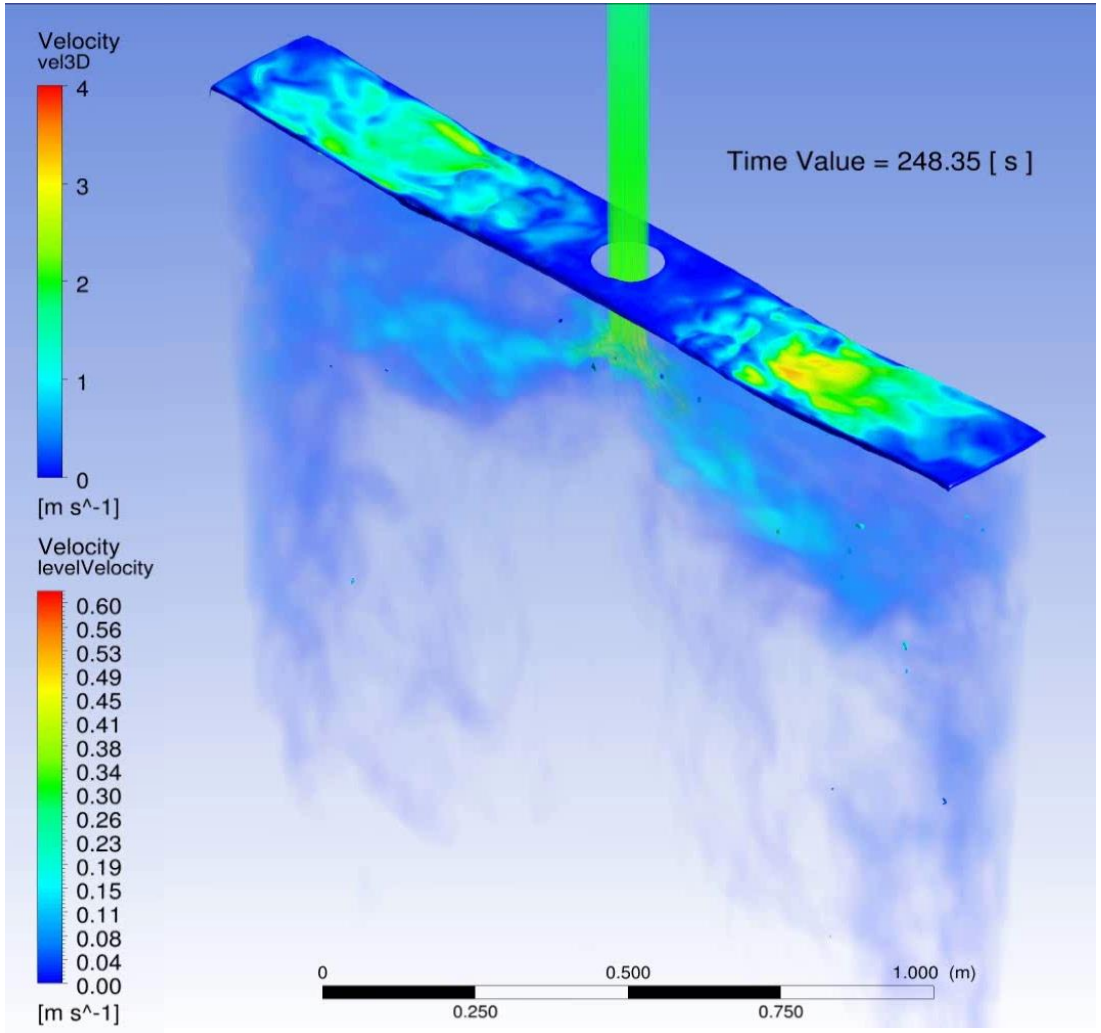

**Single-nail dipping test by Sidenor**

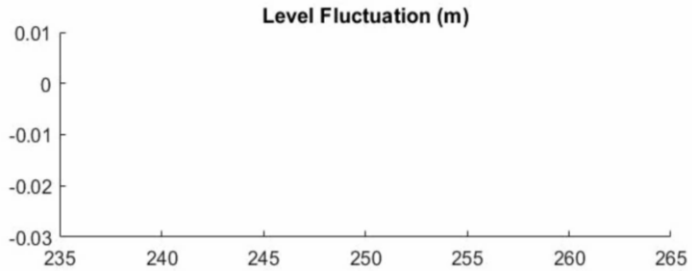
| Current, [A] | Avg Lump Height, [mm] | Avg Lump Thickness, $\phi_{lump}$ [mm] | Avg Surface Velocity, [m/s] |
|---|---|---|---|
| 400 | 2.88 | 14.28 | 0.18 |
| 500 | 5.79 | 15.34 | 0.25 |
| 600 | 6.20 | 17.28 | 0.24 |

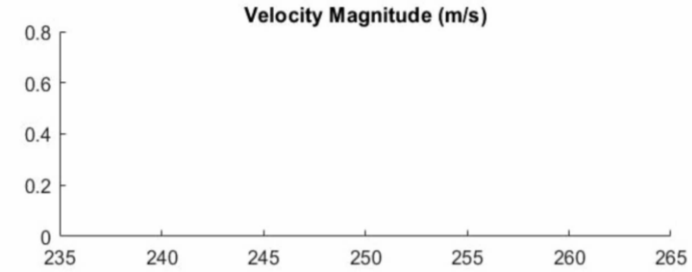
**From Yang et al. Steelsim 2019**

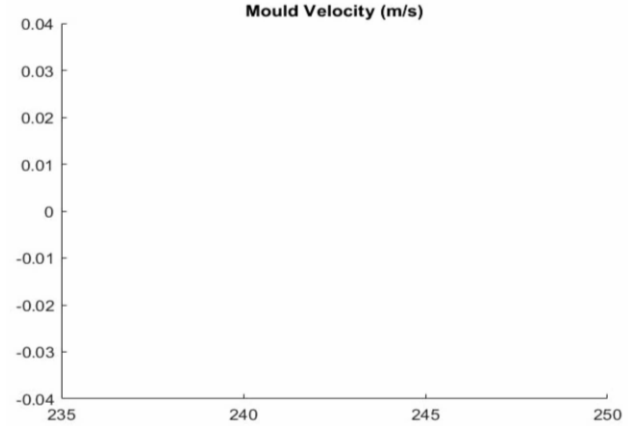
# Example 1. Slag entrapment in slabs

- **VOF** for capturing the **metal level instability** and **slag entrainment**



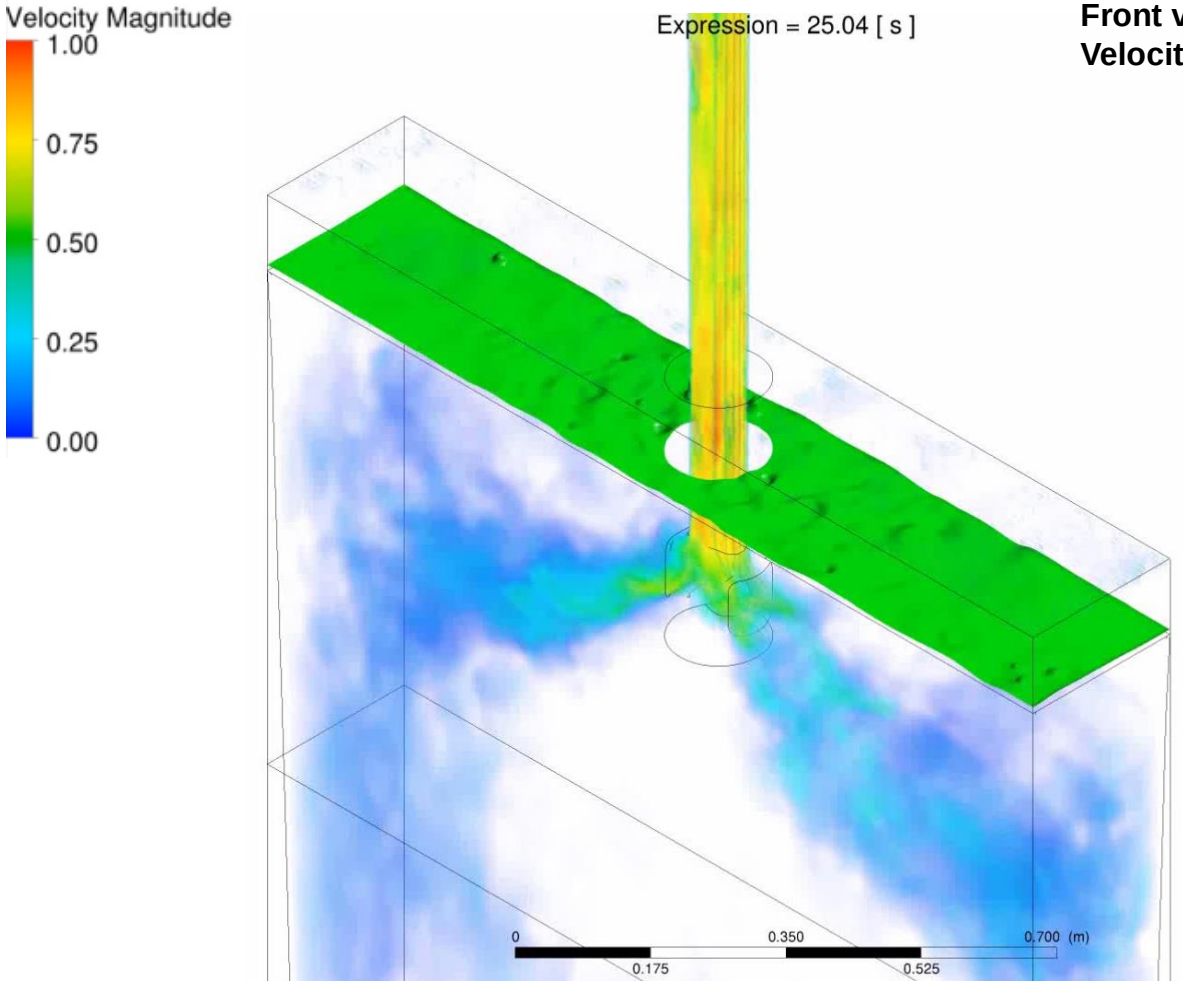



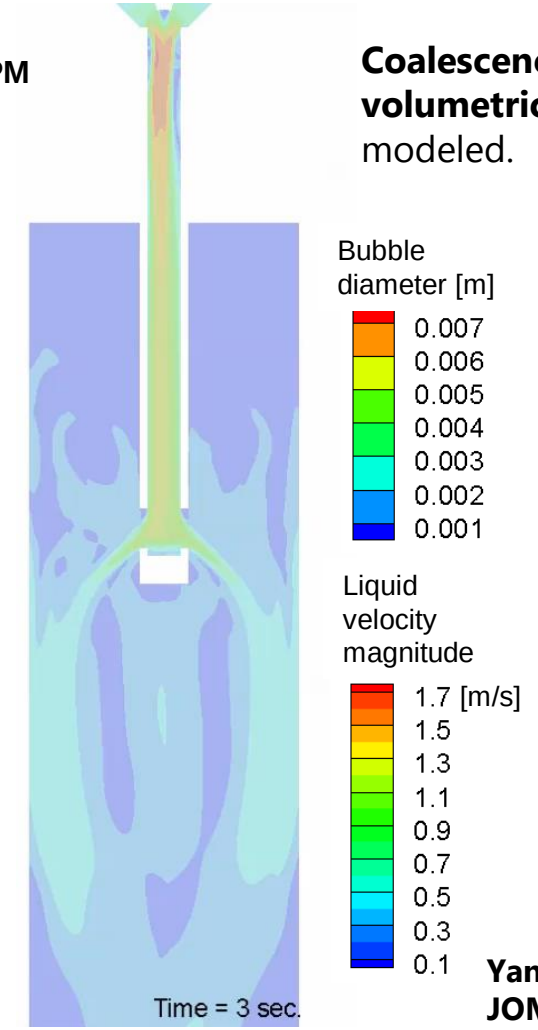



# Example 2. Pinhole defects

- **DPM** for bubble tracking, VOF for metal level
- **Capture criteria** can be applied for **bubble entrapment** on shell




**Front view**
**Velocity field + DPM**




**Coalescence**, **breakup** and **volumetric expansion** are modeled.

Bubble diameter [m]
0.007
0.006
0.005
0.004
0.003
0.002
0.001

Liquid velocity magnitude
1.7 [m/s]
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1

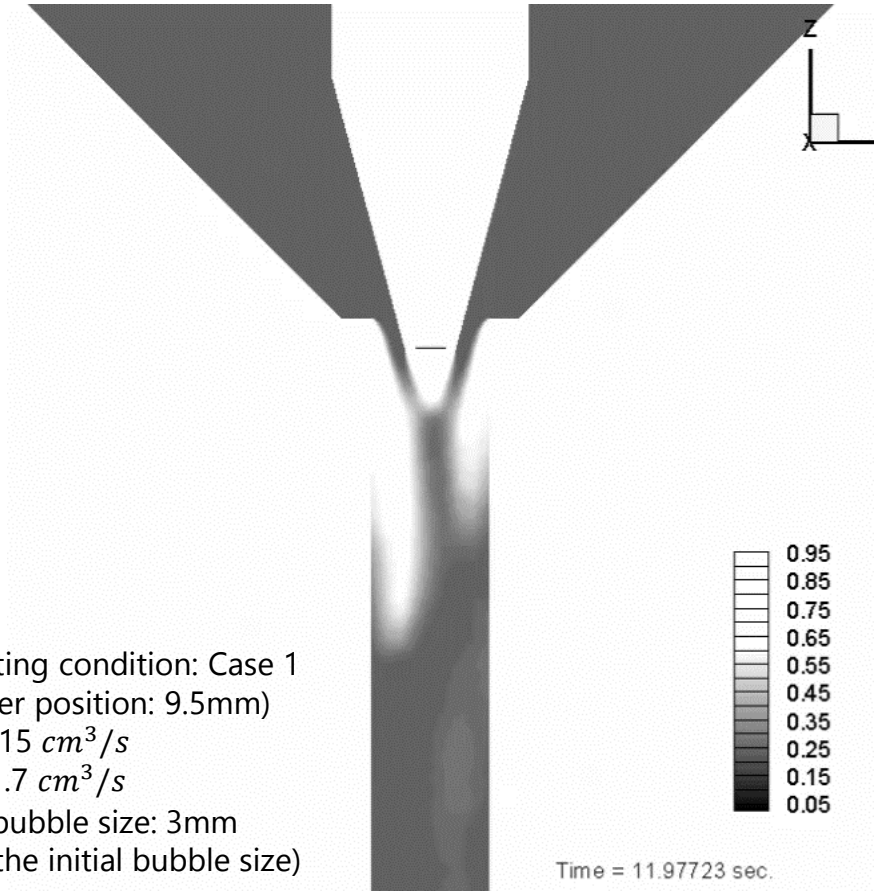
**Yang, Vanka and Thomas, JOM (2019)**

# Example 3. Gas pocket formation

- **EE model is used for Gas pockets** formed at **recirculation zones**

**From Yang, Vanka and Thomas, JOM (2019) for simulation**
**From Timmel et al. Metran B (2015) for measurement**

**Simulation result**




Operating condition: Case 1
(stopper position: 9.5mm)
$Q_l = 115\ cm^3/s$
$Q_g = 1.7\ cm^3/s$
Input bubble size: 3mm
(from the initial bubble size)

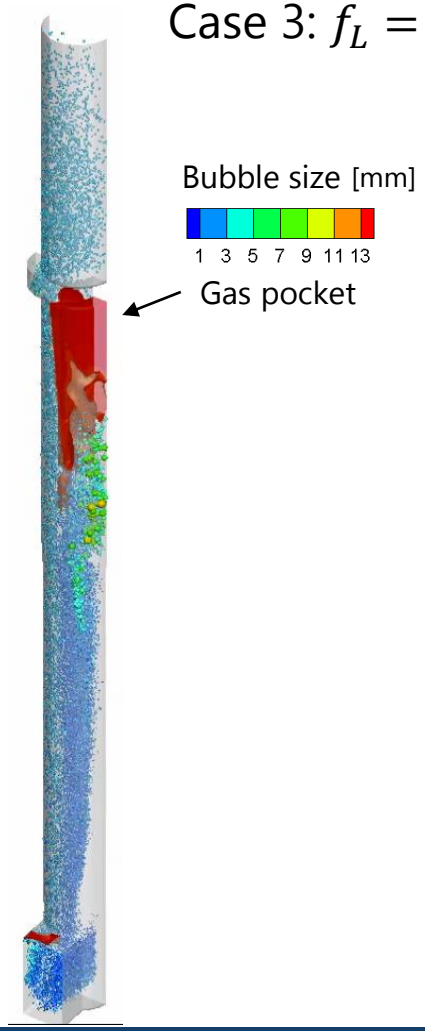
**Dresden measurement video by X-ray shots**

# Example 4. Argon bubble size distribution

- **EEDPM** model is used for **prediction of bubble size distribution**
- **EE** for **large gas pockets, DPM** for **small bubbles**

**From Yang, Vanka and Thomas, JOM (2019)**

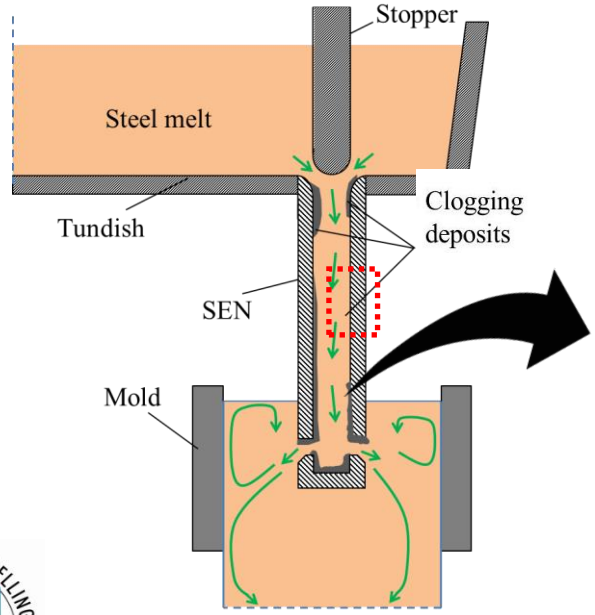
Case 3: $f_L = 75\%$

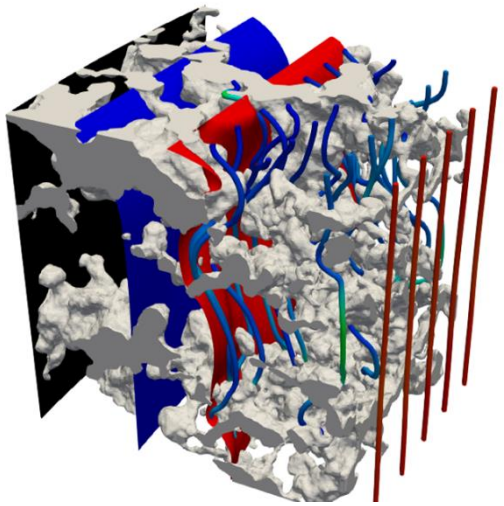


# Example 5. Nozzle clogging

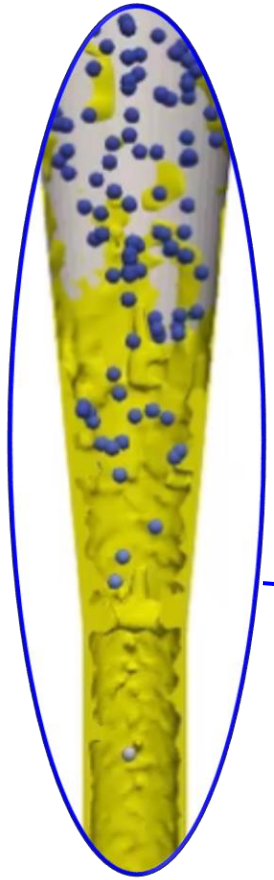
- **DPM** model for solid impurities.
- **Porosity model** for clogging.

1) Clogging is a transient phenomenon, and the growth of clog front and the melt flow interact with each other.
2) Clogging does promote solidification; Solidification unlikely occurs before clogging, but stabilizes clogging.

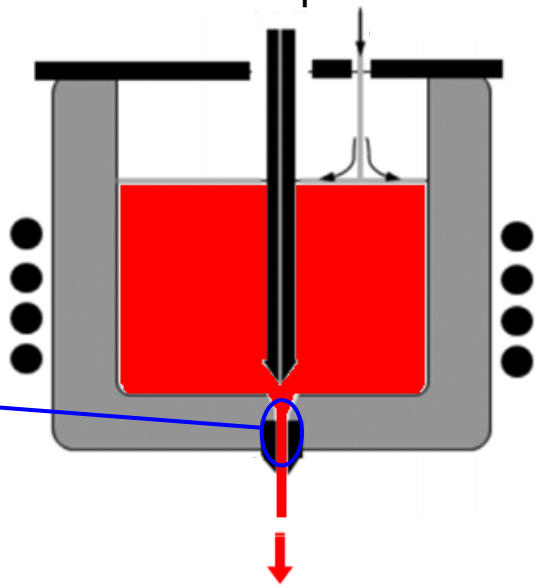


CFD simulation



Clogging phenomenon in a steel transport nozzle



Barati H., Wu M., Kharicha A., Ludwig A., Powder Techn., 2018; MMTB, 2019; Steel Res. Int., 2020.

# SUMMARY

- There are fundamental questions remaining in CC:
  - **How much gas** is in the system?
  - How is the gas **redistributed** into bubbles?
  - How does the **bubble size distribution** affect the CC process?
- Multiphase flow issues in CC can be **modeled** through a **proper selection** of multiphase flow model:
  - Understanding **limitations** of the model is important.
- **Recommendations** for selection of multiphase flow model:
  - Small bubbles: DPM
  - Large bubbles and gas pockets: EE
  - Free surface (mold level): VOF
  - Overall flow pattern: EE, mixture models
  - Aspiration & Clogging: DPM-porosity model, Bernoulli equation
  - Bubble size distribution: MUSIG models, EEDPM
- **Hybrid models** are **powerful** by taking advantages from each model
  - Hybrid between **particle-based and field-based models** is promising (e.g., EEDPM).

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# Thanks for the attention!

**Stay informed**

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