Prediction and Validation of Mold Fluid Flow and Particle Transport in Continuous Slab Casting with Electromagnetic Braking (EMBr)

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Acknowledgments

• Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Tata Steel, Goodrich, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech/Posco, SSAB, ANSYS-Fluent)

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Continuous Casting Consortium (CCC)

• Formally created in 1991, and directed by Prof. Brian G. Thomas.

• It encompasses a cooperative research effort between the University of Illinois, the Steel Industry, and the Government (NSF Project).

• The purpose is to develop comprehensive mathematical models of the continuous casting of steel slabs and to apply these models to improve understanding, optimize the process, and solve practical problems of interest to the participating members.
Contents

I. Introduction to Continuous Casting;

II. Prediction and Validation of Mold Fluid Flow and Particle Transport in Continuous Slab Particle/Bubble Capture Model (by Kai Jin);

III. Parametric Study, the Effect of EMBr and Optimize Operation Condition (by Kai Jin);

IV. Turbulent Fluid Flow simulation with FLUENT and FLUENT Speedup on Blue Waters Supercomputer (by Rui Liu);
I. Introduction to Continuous Casting

Phenomena included in the model:
1. Two-phase flow (molten steel + Ar gas)
2. Turbulent flow
3. Electromagnetic force

Figure from Brian G. Thomas and Lifeng Zhang, 2001 [1]

Figure from Okazawa et al, 2001 [2]

Responsible for >95% of the 1.4 Billion tons of steel produced every year; Harsh environment makes experiments difficult; computer models allow process to be understood and improved.
II. Prediction and Validation of Mold Fluid Flow and Particle Transport in Continuous Slab
Overall Objectives

• Improve understanding of fluid flow in the Baosteel slab-casting mold, including the effect of EMBr;

• Develop off-line CFD model to accurately model multiphase fluid flow with EMBr (prediction of flow pattern, surface velocity, etc.) and validate model by comparing with measurements at Baosteel: bubble entrapment location;

• Study Ar gas bubble behavior: predict bubble trajectories and entrapment;

• Investigate effect of EMBr, Ar gas injection, and SEN downward angle on mold flow pattern and top surface velocity;

• Apply model to optimize EMBr operation in commercial slab casters, evaluate the quality of flow pattern and provide suggestions regarding operation;
Part 1 – Experiments
(Bubble entrapment measurements at Baosteel)
Methodology of Experiment (Translated from Baosteel Report[4])

- Casting Conditions
- Samples from middle WF, ⅓ WF and NF, as shown in Fig. 1.
- Milling off steel layer by layer.
- Use 35x optical microscope to examine bubbles. Record bubble number, distribution and size.

<table>
<thead>
<tr>
<th>Mill/Grind Depth (mm)</th>
<th>Sample Layer Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>17</td>
<td>5</td>
</tr>
<tr>
<td>22</td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Casting speed (m/min)</th>
<th>Cross Section (mm)</th>
<th>EMBr</th>
<th>Ar Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>230×1300</td>
<td>ON</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF</td>
<td>YES</td>
</tr>
<tr>
<td>1.5</td>
<td>230×1250</td>
<td>ON</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF</td>
<td>YES</td>
</tr>
</tbody>
</table>

A bubble with diameter 1.45mm was found in sample from NF.
Part 2 – Numerical Simulation
Simulation Procedure

Two Steps

1. **Obtain fluid field solution:** Two-way coupled steady-state Eulerian-Lagrangian simulation (with $k$-$\epsilon$ model) was performed using FLUENT discrete phase model.

2. **Bubble trajectory tracking:** bubbles are injected into the domain and their trajectories are tracked. A stochastic model – *Discrete Random Walk model* is added to compensate the effect of turbulence dispersion of particles. No fluid iteration during this step.
Governing Equation For Fluid Flow

Steel and Ar Properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Steel</th>
<th>Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>7,000</td>
<td>0.5</td>
</tr>
<tr>
<td>Viscosity (kg/m-s)</td>
<td>0.0063</td>
<td>2.12e-5</td>
</tr>
<tr>
<td>Electrical Conductivity (S/m)</td>
<td>714,000</td>
<td>1.0e-15</td>
</tr>
<tr>
<td>Magnetic Permeability (h/m)</td>
<td>1.26x10^{-6}</td>
<td>4πx10^{-7}</td>
</tr>
</tbody>
</table>

Continuity Equation

\[
\frac{\partial u_i}{\partial x_i} = 0
\]

Steel momentum equation

\[
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + F_i
\]

Steady-State RANS Turbulence Model ($k$-$\varepsilon$)

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho u_i k) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] - \rho u'_i u'_j \frac{\partial u_j}{\partial x_i} - \rho \dot{\varepsilon}; \quad \mu_t = \rho C_\mu \frac{k^2}{\dot{\varepsilon}}
\]

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho u_i \varepsilon) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\dot{\varepsilon}}{k} \left( \rho u'_i u'_j \frac{\partial u_j}{\partial x_i} \right) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}
\]

C$_{10}$ = 1.44; \quad C$_{20}$ = 1.92; \quad C$_\mu$ = 0.09; \quad \sigma_k = 1.0; \quad \sigma_\varepsilon = 1.3

\[
\rho u'_i u'_j \frac{\partial u_j}{\partial x_i} = \mu_t \left( \nabla \vec{u} + (\nabla \vec{u})^T \right) \cdot \vec{v} \vec{u}
\]
Geometry and Boundary Conditions

**Casting Conditions**

<table>
<thead>
<tr>
<th>Location</th>
<th>Boundary Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>$V = 1.69 \text{ m/s}; 8.2% \text{ vol. fraction of Ar}$</td>
</tr>
<tr>
<td>Outlet</td>
<td>pressure 184kpa; particle captured;</td>
</tr>
<tr>
<td>Symmetry Plane</td>
<td>Symmetry;</td>
</tr>
<tr>
<td>Meniscus</td>
<td>free-slip wall; particle escape;</td>
</tr>
<tr>
<td>NF and WF</td>
<td>no-slip wall; steel mass &amp; momentum sink; particle capture criterion UDF;</td>
</tr>
<tr>
<td>SEN Walls</td>
<td>no-slip wall; particle reflect;</td>
</tr>
</tbody>
</table>

**Domain:** ½ (SEN + Mold + Slide Gate + Solid Shell)

- **Velocity inlet**
  - Bubble injection
  - Ar volume fraction 8.2%

- **No-slip wall, bubble reflect**
  - Bubble injection

- **Symmetry**
  - free slip wall; bubble escape;
  - no slip wall; Steel Mom./Mass sink;
  - Bubble capture criterion

- **Mold Region**
  - Pressure Outlet; Bubble captured;
  - 0.23m: No slip wall; Steel Mom./Mass sink;
  - 3.05m: free slip wall; bubble escape;
  - 2.5m: no-slip wall, bubble reflect
Mesh with Steel Shell in Domain Created Using ANSYS ICEMCFD, ~1.2 Million Hexahedron cells

- Mesh Created in ANSYS ICEMCFD
- ~1.2 million structured cells
- ½ (SEN + Mold + Slide Gate + Steel Shell)

Sym. Surface View
Smooth Shell

Solid Shell

Meniscus View
Bubble Distribution

As stated before, there are **2 Steps** in the simulation:

Step-1: Two-way coupled Eulerian-Lagrangian simulation to obtain fluid field;

Step-2 Particle are randomly released from inlet; trajectories are tracked by Random Walk Model.

Diameter of injected bubble and their volume fraction

The distribution of Injected bubbles satisfies Rosin-Rammler distribution, with mean diameter 3mm.

In step – 1, two-way coupled simulation with **5 different groups of bubbles**

In step – 2, **10 different groups of bubbles** are injected and tracked.

**244,239** bubbles are injected in total, among them there are **47,564** bubbles with diameter 1mm.

\( \alpha \) is total Ar volume fraction at injection point which is 8.2% in this case.
Two Different Capture Models

**Simple capture criterion** (touch=capture) is used at beginning. Particles (bubbles) are captured when they touch NF or WF.

**Advanced capture criterion** is implemented and the criterion is described both in Quan Yuan’s PhD thesis (2004)[5] and Sana Mahmood’s Master thesis (2006)[6]. A flow chart of capture criterion is given in figure below. PDAS used in the criterion is obtained from Sana Mahmood’s Master thesis (2006)[8] as well.

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**Advanced Capture Criterion (Figure from Sana Mahmood, Master thesis, 2006[8])**

**PDAS vs. Distance below meniscus (Figure from Sana Mahmood, Master thesis, 2006[8])**
Forces Related to Capture Criterion

\[ R_p \]  particle radius
\[ V_{sol} \]  solidification velocity
\[ r_d \]  dendrite tip radius
\[ h_o \]  distance between dendrite tip and particle
\[ a_o \]  atomic diameter of the liquid
\[ C_o \]  sulfur content of steel
\[ D_s \]  diffusion coefficient of sulfur in steel
\[ k \]  distribution coefficient

Forces on particles [5,6]:
\[ F_B = \left( \rho_{steel} - \rho_{Ar} \right) g \frac{4}{3} \pi R_p^3 \]

Buoyancy force pointing upward
\[ F_{lub} = 6 \pi \mu V_{sol} \frac{R_p^2}{h_o} \left( \frac{r_d}{r_d + R_p} \right)^2 \]

Lubrication force acts on the particle along particle’s radius towards dendrite tip
\[ F_I = 2 \pi \Delta \sigma_o \frac{r_d R_p}{r_d + R_p} \frac{a_o^2}{h_o^2} \]

\[ \Delta \sigma_o = \sigma_{sp} - \sigma_{sl} - \sigma_{pl} \]

Van der Waals force pushes particle away from dendrite tip
\[ F_{Grad} = -\frac{m \beta \pi R_p}{\xi^2} \left\{ \frac{\xi^2 - R_p^2}{\beta} \ln \left( \frac{\xi + R_p}{\xi - R_p} \right) \left[ \alpha \left( \frac{\xi - R_p}{\xi + R_p} + \beta \right) \right] + 2 \frac{2R_p}{\alpha} - \frac{\beta}{\alpha} \ln \frac{\alpha \left( \frac{\xi - R_p}{\xi + R_p} + \beta \right)}{\alpha \left( \frac{\xi + R_p}{\xi - R_p} + \beta \right)} \right\} \]

Interfacial gradient force push particle toward solidification front

\[ \alpha = 1 + nC_o \]
\[ \beta = n r_d \left( C^* - C_o \right) \]
\[ \xi = R_p + r_d + h_o \]
\[ r_d V_{sol} \]
\[ 2D_s = \frac{C^* - C_o}{C^*(1-k)} \]
One Simulation Result of Case – 1: Bubbles Captured by NF and WF with **Simple** Capture Criterion

**WF - I.R.**

- **Layer 1**
- **Layer 2**
- **Layer 3**
- **Layer 4**
- **Layer 5**
- **Layer 6**

**Bubble Diameter (µm)**
- **5000**
- **4000**
- **3000**
- **2000**
- **1000**
- **300**
- **200**
- **100**
- **80**
- **40**
- **25**

**Distance from Meniscus (m)**

- **X (m)**
- **0**
- **0.5**
- **1**

**WF - O.R.**

- **Layer 1**
- **Layer 2**
- **Layer 3**
- **Layer 4**
- **Layer 5**
- **Layer 6**

**Bubble Diameter (µm)**
- **5000**
- **4000**
- **3000**
- **2000**
- **1000**
- **300**
- **200**
- **100**
- **80**
- **40**
- **25**

**Distance from Meniscus (m)**

- **X (m)**
- **0**
- **0.5**
- **1**

**NF**

- **Layer 1**
- **Layer 2**
- **Layer 3**
- **Layer 4**
- **Layer 5**
- **Layer 6**

**Bubble Diameter (µm)**
- **5000**
- **4000**
- **3000**
- **2000**
- **1000**
- **300**
- **200**
- **100**
- **80**
- **40**
- **25**

**Distance from Meniscus (m)**

- **Y (m)**
- **-0.2**
- **0**
- **0.2**

**Center Region**
**Quarter Region**

- **10,605 Bubbles Captured**
- **4.3% of all injected bubbles**

- **5,558 Bubbles Captured**
- **2.3% of all injected bubbles**

- **4,808 Bubbles Captured**
- **2.0% of all injected bubbles**

**20,971 captured in total**
One Simulation Result of Case – 2 Bubbles Captured by NF and WF with **Advanced** Capture Criterion

**WF - I.R.**

- **Layer 1**
- **Layer 2**
- **Layer 3**
- **Layer 4**
- **Layer 5**
- **Layer 6**

**WF - O.R.**

- **Layer 1**
- **Layer 2**
- **Layer 3**
- **Layer 4**
- **Layer 5**

**NF**

- **Layer 1**
- **Layer 2**
- **Layer 3**
- **Layer 4**

**Distance from Meniscus (m)**

- **Center Region**
- **Quarter Region**

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**Bubble Diameter (µm)**

- Red: 300
- Orange: 200
- Yellow: 100
- Green: 80
- Light Blue: 40
- Dark Blue: 25

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**Captured Bubbles**

- **WF - I.R.**
  - 6,515 Bubbles Captured
  - 2.7% of all injected bubbles

- **WF - O.R.**
  - 3,880 Bubbles Captured
  - 1.6% of all injected bubbles

- **NF**
  - 3,274 Bubbles Captured
  - 1.3% of all injected bubbles

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**Total Captured Bubbles**

- **13,669 captured in total**
Compare the Mean Capture Results with Plant Measurement (Mean result of 10 Simulations)

Note: the diameter of the bubble found in experiment of a 2D slice is converted to 3D size following procedure proposed by Simon N. Lekaka, etc. [13]
Captured Bubble sizes – compare 2 criteria (Mean of 10 simulations)

Number of Bubbles Captured by Simple and Advanced Capture Criteria vs. Bubble Diameters

- Both capture criteria predict similar capture rate for small bubbles ($d_i \leq 0.1$mm).
- **Simple capture criterion** always predict higher capture rate for all different bubbles.
- **Simple capture criterion dramatically over predict** (more than 100 times over-predicted) capture rate for bubbles $d_i > 0.1$mm.
Capture of Large Bubbles

47,564 bubbles with $d_p=1\text{mm}$ were injected and a summary of results are listed in the table below.

<table>
<thead>
<tr>
<th>Total Injected</th>
<th>Injected $d = 1\text{mm}$</th>
<th>Criteria</th>
<th>Captured Bubbles Total</th>
<th>Captured Bubbles $d = 1\text{mm}$</th>
<th>Capture Rate for $d = 1\text{mm}$</th>
<th># captured large bubble</th>
<th># captured bubble total</th>
</tr>
</thead>
<tbody>
<tr>
<td>244,239</td>
<td>47,564</td>
<td>Simple</td>
<td>20,971</td>
<td>2749</td>
<td>5.8%</td>
<td>$\frac{2749}{20971}$</td>
<td>= 13%</td>
</tr>
<tr>
<td>244,239</td>
<td>47,564</td>
<td>Adv.</td>
<td>13,669</td>
<td>43</td>
<td>0.09%</td>
<td>$\frac{43}{13669}$</td>
<td>= 0.3%</td>
</tr>
</tbody>
</table>

- Relative Capture Rate: plant measurement shows that the captured large bubbles ($d_p > 1\text{mm}$) is **0.5%** (2 bubbles out of ~400 bubbles found in experiment).

  - compare simulation results: advanced -- 0.3%, simple -- 13%

- Large bubble capture location: plant measurement shows the distance of captured large bubbles are within 2mm from the outer surface which is no more than 1cm below meniscus. Advanced capture criterion also predict large bubbles got captured at the very top of the meniscus.
Large Bubbles ($d_p = 1\text{mm}$) Captured by NF and WF with Simple Capture Criterion

![Diagram showing bubble capture in different layers and regions.](image)
Large Bubbles ($d_p=1\text{mm}$) Captured by NF and WF with Advanced Capture Criterion

WF - I.R.

WF - O.R.

Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6

Center Region
Quarter Region

33 Bubbles Captured

2 Bubbles Captured

8 Bubbles Captured

O.R.  I.R.
Conclusions

- Two bubble capture criteria are implemented into FLUENT by using UDFs, combined with FLUENT DPM model to predict bubble trajectories.

- Simple capture criterion
  Greatly overpredicts Ar bubbles trapped; this demonstrates large frequency of bubbles that touch the dendritic interface, and are washed away without being captured;

- Advanced capture criterion
  1. Correctly predicts large bubbles (diameter > 1mm) are very difficult to be captured (measured relative capture rate less than 0.5%, predicted less than 0.3%);
  2. Correctly predicts location of large bubbles will be captured very close to the meniscus;
  3. Predicted captured bubble sizes generally match measurements;
  4. Trend of decreasing size with distance below meniscus matched.
III. Parametric Study, the Effect of EMBr and Optimize Operation Condition
Effect of EMBr on Flow Pattern

No Magnetic Field

Magnetic Field: top coil 400A, bottom 600A
Effect of Ar Injection on Flow Pattern

8% Ar Gas

16% Ar Gas
Effect of SEN Downward Angle on Flow Pattern

15° SEN downward

25° SEN downward

Distance below SEN inlet (m)

velocity-magnitude: 0.00 0.04 0.08 0.12 0.16 0.20 0.24 0.28

0.60 0.55 0.50 0.45 0.40 0.35 0.30 0.25 0.20 0.15 0.10 0.05 0.00
Conclusions

- Fluent are used to perform parametric studies to investigate the effect of 1) SEN downward angle, 2) EMBr, and 3) Ar volume fraction on flow pattern in commercial caster.

- Results shows top surface velocity can be increased by:
  1) Reducing SEN downward angle;
  2) Turning off EMBr (upper ruler of FC mold);
  3) Increasing Ar volume fraction;

- Turning off EMBr, the maximum velocity on the top surface increases from 0.16 m/s to 0.3m/s (~85% increase, surface velocity ends in 0.2-0.4 m/s range, good for steel quality.[8])

- Reducing the downward angle from 25° to 15°, top surface velocity increase from 0.1m/s to 0.16m/s (~60% increment).
IV. Turbulent fluid flow simulation with FLUENT and FLUENT speedup on BlueWaters Supercomputer (by Rui Liu);
Fluid Flow with Free Surface

Steel only

Steel and argon
DES Simulated Transient Flow Pattern (quasi-steady state)

Center plane velocity distribution*

*video simulation performed on Dell workstation
Comparison of Simulated and Measured Mold Level

Pressure method:

\[ \Delta h = \frac{p - p_0}{\rho_L g} \]

- \( p_0 \) is the static pressure at starting time (160 sec in current case)
- Pressure at quarter mold point at meniscus is used in current calculation

• Results from both methods match reasonably well with measured mold level
DES Simulation with non-optimal dithering
FLUENT Speedup on Blue Waters

Speedup relative to 1-core on high-end workstation*

*Performance is for simple pressure-based top surface level: Almost no speedup with moving-grid free surface method
Conclusions

• Prediction of bubble trajectory and capture in commercial caster
  1. Two bubble capture criteria are implemented into FLUENT DPM model by using UDFs;
  2. Advanced capture criterion matches with plant measurements better than simple capture criterion.

• Parametric studies using FLUENT, to increase top surface velocity in caster:
  1. Decrease SEN downward angle;
  2. Turn off EMBr;
  3. Increase Ar volume fraction;

• FLUENT on BlueWaters Supercomputer
  1. Transient turbulent fluid flow simulations with UDFs;
  2. FLUENT performs well on BlueWaters, if care is taken in problem setup;
  3. Speed-up of ~100X for ~200 CPU processors with fixed grid.
References