Effect of EMBr on Flow and Particle Capture and Parametric Studies of Transient Flow with LES on GPU

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Outline

• Multi-GPU CUFLOW development

• Parametric study: LES simulations of effect of EMBr on fluid flow in the mold at different casing speed

• Validation of particle capture criterion

• Effect of magnetic field on particle capture
Configuration of BWs XK node and Our Lab Workstation

Currently, two versions of CUFLOW, CPU and GPU versions:
- CPU version, run on multi-CPU PC (data communication through MPI)
- GPU version, run on multi-GPU PC and multi-CPU&GPU pair supercomputer (eg. Blue Waters)

### PC - 4GPU Workstation vs. Blue Waters Supercomputer

<table>
<thead>
<tr>
<th></th>
<th>PC - 4GPU Workstation</th>
<th>Blue Waters Supercomputer</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Nodes</td>
<td>1</td>
<td>4224</td>
</tr>
<tr>
<td>Node CPU</td>
<td>Xeon E5-2650v2 Ivy Bridge, 2.60 GHz, 8 cores</td>
<td>AMD 6276, 2.3 GHz, 16 cores</td>
</tr>
<tr>
<td>GPU/Node</td>
<td>4 × Nvidia Tesla C2075, 4 × 5 GB, 575 MHz</td>
<td>1 × Nvidia Tesla K20x, 1 × 6 GB, 732 MHz</td>
</tr>
</tbody>
</table>

**Configuration of 4GPU Workstation**

- **Setup**: Virtual machine, mimic supercomputers
- **Configuration**: 2 nodes

**Validation 1 - Problem Setup**

- **Problem Setup**: 3D lid-driven Cavity Flow, Re = 1000, on 4 GPUs
- **Grid dimensions**: 256x256x256 total ~16.8 million cells
- **Multigrid**: geometric multigrid with 6 grid levels
- **Geometry**: Unit Cube
- **Boundary Conditions**: no-slip wall; top lid velocity \( U_0 \) in z direction

Domain decomposition, uniformly decomposed in z direction, as below:

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**Validation - 1 Results**

- For this 16.8 million cells, 4 GPUs, 0.678s/timestep, takes about ~18 hours to simulate 100 sec flow time.
- Velocities in symmetry plane of 4-GPU simulation ($256^3$) match exactly with single GPU results with different mesh refinements, ($64^3$, $128^3$) and with previous work Ku et al.


**Validation 2 – Variable Viscosity Validation**

- Lid-Driven Cavity Flow, Re=100, power-law behavior index is 0.5 (shear thinning fluid), using 4 GPUs.
- A uniform grid of $128 \times 128 \times 512 \sim 8.4$ million cells, using 7 level multigrid, 5 sweeps and 5 V-cycles
- Boundary Conditions: no slip wall; $y=1$ wall moving with speed $U_0$ in x direction;
- Assume boundary effect is negligible, the velocity on symmetry plane is compared with available 2D results (Because no 3D validation results available in literature).
Validation 2 – Results Non-Newtonian Module Validation

- Centerline velocities are compared with published results [1-4] and our old CUFLOW validation run (same setup, same grid size).
- Timing: old CUFLOW, 1GPU 1.41s/timestep, new CUFLOW on 4 GPUs, 0.34 s/timestep, speedup compared with old 1GPU CUFLOW is 4.14 (greater than 4 because some data structure improvement, the memory access is more efficient)


Speed Up and Comparison of BlueWaters XK Node and Our 4GPU Workstation

CUFLOW on BWs XK node and 4GPU WorkStation
3D Lid-Driven Cavity 128x128x512~8.4million cells

- Lab CPU is ~2.5 times faster than BW CPU;
- Tesla K20x is ~1.5-2.0 times faster than Tesla C2075;
- On BWs, 1 GPU vs. serial run on 1 core speed up is ~42x;
- One BWs XK node, 1 GPU is 13.4x faster than 4 CPU parallel execution;
- FLUENT, same problem one core on BWs estimated to be ~190 days which is 633 times slower than CUFLOW 4GPU parallel run on our Lab PC; but FLUENT with parallel run using all 32 cores in one BW XE node will make it 6 days which means ~20 times slower (assuming FLUENT has perfect scaling) than CUFLOW 4GPU runs on Lab PC;
Part II - LES simulations of Effect of EMBr on Fluid Flow in the Mold at different Casing Speed

Objectives

- Use the new multi-GPU code to investigate the effect of EMBr on fluid flow in Baosteel caster with different casting speed, then study transient flow behavior in mold and level fluctuations at meniscus region and provide suggestions regarding operation.

Geometry, mesh and BCs

- Full-mold domain with SEN: $176 \times 32 \times 800 = \sim 4.5\text{million cells}$, uniform grid.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Cell Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_x$ – Mold Thickness</td>
<td>230 ( \Delta x = 7.67 )</td>
</tr>
<tr>
<td>$L_y$ – Mold Width</td>
<td>1300 ( \Delta y = 7.47 )</td>
</tr>
<tr>
<td>$L_z$ – Domain Length</td>
<td>6000 ( \Delta z = 7.50 )</td>
</tr>
</tbody>
</table>

- Boundary Conditions:
  - SEN top: velocity inlet;
  - Bottom: zero derivative of velocity;
  - WF and NF: moving downward with casting speed (no shell);
  - Top surface and walls: no penetration and no slip.

- Note the SEN inlet area is the “eye-shaped” intersected region of two circles to include the slide gate.
### Parametric Study – Case Conditions

Mold Thickness **230mm** and Width **1300mm**; SEN Downward angle **15°**

<table>
<thead>
<tr>
<th></th>
<th>Casting Speed Vc (m/min)</th>
<th>Submergence Depth (mm)</th>
<th>EMBr Top Coil Current (A)</th>
<th>EMBr Bottom Coil Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>210</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>160</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>1.5</td>
<td>160</td>
<td>0</td>
<td>600</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>160</td>
<td>0</td>
<td>850</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>160</td>
<td>400</td>
<td>600</td>
</tr>
<tr>
<td>6</td>
<td>1.8</td>
<td>160</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>1.8</td>
<td>160</td>
<td>0</td>
<td>850</td>
</tr>
<tr>
<td>8</td>
<td>1.8</td>
<td>160</td>
<td>400</td>
<td>600</td>
</tr>
</tbody>
</table>

- All use **6 GPUs**;
- Initial velocity = zero, **timestep** is **0.0002s**;
- Simulated **42s** for all cases, allow **12s** for flow to develop;
- Time-averaged results are performed from **12s to 42s**, sample frequency **25Hz (data saved every 0.04s)**;

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**Magnetic Field: equations**

*curve fit of measurements*

**T400 / B600** (z=0 at meniscus), -1.25<z<0.5, other places 0, Unit z(m) and B(Tesla)

\[ B = 0.005651 + (-0.1761) \cos(z \cdot 3.497) + (-0.06336) \sin(z \cdot 3.497) + (-0.06226) \cos(2z \cdot 3.497) + 0.08456 \sin(2z \cdot 3.497) + 0.02178 \cos(3z \cdot 3.497) + 0.02742 \sin(3z \cdot 3.497) \]

**T000 / B600** (z=0 at meniscus), -1.25<z<0.5, other places 0, Unit z(m) and B(Tesla)

\[ B = 0.029730 + (-0.1158) \cos(z \cdot 3.582) + (-0.06543) \sin(z \cdot 3.582) + (-0.03495) \cos(2z \cdot 3.582) + 0.05917 \sin(2z \cdot 3.582) + 0.02027 \cos(3z \cdot 3.582) + 0.01087 \sin(3z \cdot 3.582) \]

**T000 / B850** (z=0 at meniscus), -1.25<z<0.5, other places 0, Unit z(m) and B(Tesla)

\[ B = 0.038420 + (-0.1458) \cos(z \cdot 3.586) + (-0.08316) \sin(z \cdot 3.586) + (-0.04366) \cos(2z \cdot 3.586) + 0.07488 \sin(2z \cdot 3.586) + 0.02564 \cos(3z \cdot 3.586) + 0.01328 \sin(3z \cdot 3.586) \]
Governing Equations and Steel Properties

- Continuity Equation $\nabla \cdot \vec{u} = 0$
- Momentum equation (LES Coherent-structure Smagorinsky (CSM) Model)
  $$\rho \left[ \frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \vec{u} \right] = \nabla p + \left( \mu + \mu_{sgs} \right) \nabla^2 \vec{u} + \vec{F}$$
  - $\vec{u}$ Steel velocity
  - $\rho$ Steel density
  - $\mu$ Steel viscosity
  - $\mu_{sgs}$ Sub-grid scale viscosity
- MHD Equations – Potential Method
  $$\vec{F} = \vec{J} \times \vec{B}_0$$
  $$\nabla^2 \Phi = \nabla \cdot (\vec{u} \times \vec{B}_0)$$
  $$\vec{E} = -\nabla \Phi$$
  $$\vec{J} = \sigma (\vec{E} + \vec{u} \times \vec{B}_0)$$
  $$\nabla \cdot \vec{E} = 0$$

Properties of Steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>7,000</td>
</tr>
<tr>
<td>Viscosity (kg/m-s)</td>
<td>0.0063</td>
</tr>
<tr>
<td>Electrical Conductivity (S/m)</td>
<td>714,000</td>
</tr>
<tr>
<td>Magnetic Permeability (h/m)</td>
<td>1.26*10$^{-6}$</td>
</tr>
</tbody>
</table>

Effect of Submergence Depth On Velocity (Simulations 1 and 2) (no EMBr, Vc=1.5m/min)

- Velocity magnitude contours at center plane (m/s)
- **Deeper** submergence has slightly (~5%) **higher** surface velocity.

Max top surface velocity: ~0.43m/s

Max top surface velocity: ~0.41m/s
Effect of EMBr
(Simulations 2 to 5)
(160mm Submergence, Vc = 1.5m/min)

- Velocity magnitude contours at center plane (m/s)
- Bottom EMBr only surface velocity reduced by ~67%, both top and bottom top surface velocity reduced by ~90%

Top Surface Time Averaged Velocity Magnitude for All Cases (Simulations 1 to 8)
Effect of EMBr on Transient flow in Mid and Top Surfaces (160mm Submergence, $V_c = 1.8$m/min) (Simulations 6 and 7)

- Transient animation, contour of velocity magnitude (m/s)
- Top surface velocity reduced by ~67% with bottom coil current 850A

<table>
<thead>
<tr>
<th>VC1.8m/min-SD160mm-<strong>NoEMBr</strong></th>
<th>VC1.8m/min-SD160mm-<strong>B850</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Time averaged Max top surface velocity: (-0.51\text{m/s})</td>
<td>Time averaged Max top surface velocity: (-0.17\text{m/s})</td>
</tr>
</tbody>
</table>

Effect of EMBr on Time-Averaged flow in Mid and Top Surface (160mm Submergence, $V_c = 1.8$m/min) (Simulations 6 and 7)

- Time averaged result, casting speed 1.8m/min
- Contour of velocity magnitude (m/s)

<table>
<thead>
<tr>
<th>No EMBr</th>
<th>B850</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max top surface velocity: (-0.51\text{m/s})</td>
<td>Max top surface velocity: (-0.17\text{m/s})</td>
</tr>
</tbody>
</table>
EMBr Effect on Flow Pattern
(160mm Submergence, Vc = 1.8m/min)
(Simulations 6 to 8)

- Stream lines and contours of velocity magnitude (m/s)
- EMBr lowers surface velocity and brings recirculation regions closer to the jet

No EMBr

B850

T400 / B600

With magnetic field and this high casting speed, the lower recirculation zone shrinks to a small vortex below the jet. Agreed with previous LES simulations by R-Singh[1].

EMBr Effect on Flow Pattern in Top Surface
(160mm Submergence, Vc = 1.8m/min)
(Simulations 6 to 8)

- Top surface velocity contour (unit m/s)
- Only apply bottom EMBr (current 850A) reduce top surface velocity by ~67%, with both top and bottom EMBr (400A and 600A) reduce surface velocity by ~82%
EMBr Effect on Level Fluctuation at Top Surface
(160mm Submergence, $V_c = 1.8m/min$)

Contour plot of surface level fluctuation $h$, unit: m

Effect of EMBr on top-surface fluctuations:
- lowers surface level fluctuations by 50%
- flattens the shape

Pressure Fluctuations at 3 Different Points with $V_c = 1.5m/min$ and submergence depth 160mm

- EMBr reduce pressure fluctuations by 25%-40% at region 1cm below top surface
- More effective in reducing fluctuations at region far away from SEN;

Locations of P1, P2, P3 (1cm below meniscus)

EMBr $s$ of P3
- No EMBr 82.5
- B600 61.3
- B850 60.3
- T400B600 55.1

EMBr $s$ of P2
- No EMBr 91.4
- B600 57.0
- B850 55.7
- T400B600 50.9

EMBr $s$ of P1
- No EMBr 97.0
- B600 56.7
- B850 55.6
- T400B600 50.7
Conclusions of Part II

- With small submergence depth (160 and 210), increasing submergence depth increases surface velocity slightly, with same flow pattern;
- EMBr causes center of all 4 recirculation regions to move closer to the jet;
- Applying bottom-only B600 EMBr reduces top surface velocity by 60% (from \(0.45\) to \(0.16\)m/s at 1.5m/min). Applying B850 makes flow too slow (0.??m/s).
- Applying bottom-only B850 EMBr reduces top surface velocity by \(\sim 70\)% (from \(0.6\) to \(0.2\)m/s at 1.8m/min);
- For both casting speed 1.5 &1.8m/min, high strength top EMBr makes meniscus flow very small (less than 0.1m/s) and is likely not a good practice in operation;
- At higher casting speed (1.8m/min) applying only bottom EMBr lowers surface level fluctuations by 50% (from \(\sim 2\)cm to \(\sim 1\)cm) and flattens the shape as well.
- With \(V_c=1.8\)m/min and No EMBr, time-averaged max top-surface velocity is 0.51m/s, transient simulation shows at \(\frac{1}{4}\) region of the top-surface velocity can be \(\sim 20\)% higher (\(\sim 0.6\)m/s);
- Pressure fluctuations slightly below top surface show that w/o EMBr, region close to NF has larger pressure fluctuations. EMBr is more effective (about 2 times more effective) in suppressing fluctuations at region far away from SEN.
Part III & IV – Study of Effect of EMBr on Bubble Capture in Caster

Objectives

- Use advanced capture criterion to study the effect of EMBr on Ar gas bubble behavior: predict bubble trajectories and entrapment;

- Compare model prediction and measurements with EMBr (without EMBr was presented in 2013)

- Evaluate the distribution of captured particles, and provide suggestions on plant operation.

Casting Conditions

Two new Simulations (2 and 3)

<table>
<thead>
<tr>
<th>EMBr</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No EMBr</td>
</tr>
<tr>
<td>2</td>
<td>Bottom coil current 600 A</td>
</tr>
<tr>
<td>3</td>
<td>Top coil current 400 A &amp; Bottom coil current 600 A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Casting Conditions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold Thickness</td>
<td>230 mm</td>
</tr>
<tr>
<td>Mold Width</td>
<td>1300 mm</td>
</tr>
<tr>
<td>Submergence Depth</td>
<td>160 mm</td>
</tr>
<tr>
<td>Port Downward Angle</td>
<td>15 deg.</td>
</tr>
<tr>
<td>Casting Speed</td>
<td>1.5 m/min</td>
</tr>
<tr>
<td>Ar injection</td>
<td>8.2% vol.</td>
</tr>
</tbody>
</table>

For each case, post-tracking release 0.24 million bubbles, with random walk model. Then repeat 10 times (total 2.4 million particles are tracked for each case) and get averaged results.
Geometry and Boundary Conditions

- Velocity inlet
- Bubble injection
  - Ar volume fraction 8.2%
- No-slip wall; bubble reflect
- Symmetry
- free slip wall; bubble escape;
- Mold Region
- Pressure Outlet; Bubble captured;
- Domain: \( \frac{1}{2} \) (SEN + Mold + Slide Gate + Solid Shell)

<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>Sym. 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>

Governing Equation For Fluid Flow

- **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 \((k-\epsilon)\)**
  \[
  \frac{\partial}{\partial x_i} \left( \rho u_i \right) = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] - \rho \nu \frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_i} - \epsilon \frac{\partial u_i}{\partial x_i}
  \]
  \[
  \frac{\partial}{\partial x_i} \left( \rho \epsilon \right) = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \epsilon}{\partial x_i} \right] + C_{\mu} \frac{\epsilon}{k} \left( \rho u_i \frac{\partial u_i}{\partial x_i} - \frac{\partial u_j}{\partial x_j} \right) - C_s \rho \frac{\epsilon^2}{k}
  \]
  
  \( C_{\mu} = 1.44; \quad C_s = 1.92; \quad C_\mu = 0.09; \quad C_\epsilon = 1.3 \)

  \[
  \rho u_i u_j \frac{\partial u_i}{\partial x_j} = \mu_t \left( \nabla \bar{u} + (\nabla \bar{u})^T \right) : \nabla \bar{u}
  \]

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>
</tbody>
</table>
Particle Tracking with Random Walk Model

Equation of Motion for Particles
\[
\frac{d\vec{u}}{dt} = F_D (\vec{u} - \vec{u}_p) + g (\rho_l - \rho_p) + \vec{F}_r
\]

Re_p = \frac{\rho_d}{\rho_p} \frac{d}{2} \frac{u_l}{\mu}

F_D = \frac{18\mu C_D Re_p}{\rho_p d^2}

Spherical drag law suggested by S. A. Morsi and A. J. Alexander

\[ C_D = a_1 \frac{a_2}{Re_p} + \frac{a_3}{Re_p^2} \]

\[ a_i, a_{i+1} = \begin{cases} 0.24, 0 < Re_p < 0.1 \\ 3.690, 22.73, 0.0993, 0.1 < Re_p < 1 \to 12.22, 29.167, -3.8889, 1 < Re_p < 10 \to 0.6167, 46.50, -116.67, 10 < Re_p < 100 \to 0.3644, 98.33, -2778, 100 < Re_p < 1000 \to 0.357, 148.62, -47500, 1000 < Re_p < 10000 \to 0.46, -490.546, 578700, 5000 < Re_p < 10000 \to 0.5191, -1662.5, 5416700, Re_p > 10000 \end{cases} \]

Momentum Exchange to Fluid
\[
\vec{F} = \sum \frac{18\mu C_D Re_p}{\rho_p d^2} (\vec{u} - \vec{u}_p) \text{d}m
\]

Discrete Random Walk Model
Gaussian distributed random velocity fluctuation, \( u', v', w' \) are generated from
\[ u' = \zeta u' \quad v' = \sqrt{v'} \quad w' = \sqrt{w'} = \sqrt{2k/3} \]
\( \zeta \)– standard normal distribution random number.

\[ t_i = C_k \frac{k}{\varepsilon} = 0.15 \frac{k}{\varepsilon} \quad t_r = t_L \ln (r) \]

\[ \tau = \frac{\rho_s d^2}{18\mu} \quad t_{cross} = -\tau \ln \left( 1 - \frac{C_m k^{3/2}}{\varepsilon} \right) \]

\( r \)– uniformly distributed random number from 0 and 1. This yields a random eddy life time.

\[ \text{Yes} \]

\[ \text{interaction time reached?} \]

\[ \text{Yes} \]

\[ \text{interaction time reached?} \]

\[ \text{No} \]

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**: Particles 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
Capture Criterion

- **Advanced capture criterion** is implemented and the criterion is described both in Quan Yuan’s PhD thesis (2004) [3], Sana Mahmood’s Master thesis (2006) [4] and Thomas, Brian G., et al [5]. A flow chart of capture criterion is given in figure below.

![Advanced Capture Criterion (Figure from Sana Mahmood, Master thesis, 2006)](image1)
![A Bubble/Particle Touching 3 Dendrite Tips (Figure from Thomas, Brian G., et al [5])](image2)

Forces Related to Capture Criterion

- Theoretical solidification velocity is used on NF/WF
- Compare Shell Growth Velocity

\[ F_{\text{bu}} = \left( \rho_{\text{sol}} - \rho_{\text{p}} \right) g \frac{4}{3} \pi R_p^3 \]

Buoyancy force pointing upward

\[ F_{\text{lab}} = 6 \pi \mu N \left( \frac{R_p}{h_p} \right)^2 \left( \frac{r_d}{r_d + R_p} \right)^2 \]

Lubrication force acts on the particle along particle’s radius towards dendrite tip

\[ F_l = 2 \pi \mu \Delta \sigma \frac{r_d R_p}{r_d + R_p} a_0 \left( \frac{r_d}{r_d + R_p} \right)^2 \]

\[ \Delta \sigma = \sigma_{\text{p}} - \sigma_{\text{sol}} \]

Van der Waals force pushes particle away from dendrite tip

\[ F_{\text{vdw}} = -m \beta R_p \frac{\xi - R_p}{\sigma} \left[ \frac{\xi + R_p}{\beta} \right] \left[ \frac{a (\xi - R_p) + \beta}{a (\xi + R_p) + \beta} \right] + \frac{2 R_p}{\alpha} \left[ \frac{\xi - R_p}{\beta} \right] \left[ \frac{a (\xi - R_p) + \beta}{a (\xi + R_p) + \beta} \right] \]

Interfacial gradient force push particle toward solidification front

\[ \Delta \sigma = \frac{m \beta R_p}{\sigma} \left[ \frac{\xi + R_p}{\beta} \right] \left[ \frac{a (\xi - R_p) + \beta}{a (\xi + R_p) + \beta} \right] \]
Relate Bubble Capture Prediction with Measurement

- Which bubble can be found in a certain slice of a sample, e.g. $x_s = 9$ mm?

Need to satisfy: 

\[ x_i < x_s \text{ and } x_i + r_i > x_s \quad \text{or} \quad x_i > x_s \text{ and } x_i - r_i < x_s \]

Sample from Measurement

Bubbles/Particles Captured in Simulation

Method to Predict Number of bubbles Captured in a Slice of Sample

Task: Predict the number of bubbles captured ($n$) by a slice that is $x_s$ beneath a NF sample which has length $L$ in casting direction. Then find if $L$ is changed to $L'$, what the number ($n'$) will be?

- Use $L/V_c$ to calculate time $T$.
- Based on $T$, Ar flow rate and bubble size distribution to calculate number of bubbles need to be injected, $N$.
- Run steady-state simulation, release $N$ bubbles.
- Output the data of captured bubbles ($x_i$, $y_i$, $z_i$, $r_i$).
- Loop for all captured bubbles, set counter $n=0$.
- Output $n$ and other data (e.g. bubble diameter).
Flow Field with EMBr and Ar Gas

- Contour plot of velocity magnitude (m/s)

Small-bubble distributions with No EMBr (Diameter ≤ 0.3mm)

- Slide gate open to IR, more capture on IR due to more gas escape from IR side;
Small-bubble distributions with **B600 EMBr** (Diameter ≤ 0.3mm)

- With B600 EMBr, capture on IR and OR are more similar;
- With B600 EMBr, number of bubbles captured by NF is reduced by 48% compare with no EMBr;

Small-bubble distributions with **T400 / B600 EMBr** (Diameter ≤ 0.3mm)

- With T400 / B600 EMBr, capture on IR and OR looks very same
- With T400 / B600 EMBr, number of bubbles captured by NF is reduced by ~75% compare with no EMBr;
Large-Bubble Distributions with No EMBR (Diameter ≥1mm)

No large bubbles \( d_p \geq 1 \text{ mm} \) get captured for EMBR B600 or EMBR T400 B600 cases for 1 simulation.

Effect of EMBR on Bubble Capture (Average Number of Captured Bubble)

- 6 locations below meniscus associated with 3, 6, 9, 12, 17, 22 mm from out surface of the slab.
- Simulations predict less particles captured close to meniscus, because hook is not in the model.
**Effect of EMBBr on Bubble Capture**

(Average Bubble Diameter)

- 6 locations below meniscus associated with 3, 6, 9, 12, 17, 22 mm from out surface of the slab.

- Simulations always predict larger particle diameter, this may due to the injected bubbles are larger than that of bubbles in real caster.

- EMBr makes bubble escape from the middle region of top surface, less bias escaping of bubbles;

- Stronger EMBr make more bubbles escape from region close to SEN.
Effect of EMBr on Bubble Capture Rates and Fractions

- Bubble capture rates and fractions (averaged of 10 simulations for each case);
- EMBr has less effect on capture rates of small bubbles;
- Capture rate for small bubbles ($d_p \leq 0.1\text{mm}$) is almost the same (~70%);
- Large bubbles has very low capture fraction (<0.1%); especially with EMBr (<0.002%)

Conclusions of Part III and IV

- Current simulations predict the same trend of captured bubble diameter but the predicted average diameter is larger than measured. This may due to the assumed distribution of bubble size (mean 3mm and Rosin-Rammler distribution) may larger than that in real caster;
- Although advanced capture model is much better than simple capture model\textsuperscript{[2]}, bubble capture near the meniscus (strand surface) is still under-predicted, perhaps because hooks are not included in the model;
- Magnetic field causes more symmetrical flow distribution and bubble escape to the top surface. Without EMBr, there is significant surface cross flow from IR to OR, (due to slide gate opening towards IR causing Ar gas flow asymmetry), leading to more bubble capture on IR\textsuperscript{[2]});
- Magnetic field reduces the bubble capture rate on NF and makes more uniform capture on WF IR and OR,
- Capture rates on WF and NF are very similar (per unit area).
- Capture rates for small bubbles are MUCH larger then that of large bubbles and for bubbles less then 0.1mm the capture fraction are almost the same (~70%); large bubbles are very rarely captured even without EMBr(<0.1%);
- EMBr lowers capture rate for 1mm bubbles (from 0.1% to 0.002%)
Future Work

- Investigate the average size and distribution of Ar gas bubbles in mold and investigate a more realistic bubble distribution which can be used in future;

- Add hook capture mechanism into the advanced capture criterion and implement it into Fluent/CUFLOW.

- Implement two-way fluid and particle interaction and capture criterion into multi-GPU CUFLOW and use transient LES simulations to study the capture of bubbles/particles;

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