Electromagnetic effects on multi-phase flow in the slab casting nozzle and mold

R. Chaudhary, Brian G. Thomas
Department of Mechanical Science and Engineering,
University of Illinois at Urbana-Champaign

Seong-Mook Cho, Go-Gi Lee, Seon-Hyo Kim
Department of Materials Science and Engineering,
Pohang University of Science and Technology, Pohang,
Kyungbuk 790-784, South Korea

Project outline

• To investigate the effect of argon gas and magnetic field on turbulent nozzle & mold flow:
  – 3-D, turbulent, single-phase steel flow model
  – 3-D, turbulent, multiphase flow model (Eulerian-mixture & Eulerian-Eulerian models)
  – 3-D, Single-phase steel flow and multiphase steel-argon flow models with MHD (based on measured magnetic fields)
  – 3-D, VOF model to investigate the effect of slag-steel interface on single-phase steel flow

• Experiments were performed in real caster with Nail-board measurements (with & without magnetic field)
  – To measure free surface velocity at 10 locations along two lines parallel to wide faces at 55 mm from mid-plane
  – Surface level variations were also measured at same locations

• Perform one way coupled inclusion transport and entrapment studies. (with Rui Liu)
• Based upon knowledge gained from above modeling and experimental work, flow parameters will be fine tuned to optimize multiphase turbulent flow in real caster to minimize inclusion defects in the final steel product.
Mold schematic with dimensions and shell thickness along wide- and narrow faces

Shell thickness as a function of distance below meniscus (CON1D)

\[
S_{(WF)}(mm) = 24.0 \frac{Z(mm)}{1000V_{(cav)}} (m/\text{min}) \\
S_{(NF)}(mm) = 22.6 \frac{Z(mm)}{1000V_{(cav)}} (m/\text{min})
\]

Process parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting speed</td>
<td>1.64 m/min</td>
</tr>
<tr>
<td>Steel flow rate</td>
<td>533 LPM</td>
</tr>
<tr>
<td>Argon gas injection rate</td>
<td>9.2 SLM: STP (1 atm Pr and 273K)</td>
</tr>
<tr>
<td>Nozzle inner diameter</td>
<td>90 (at UTN top) to 80 (at bottom well) mm</td>
</tr>
<tr>
<td>Nozzle outer diameter</td>
<td>140 mm</td>
</tr>
<tr>
<td>Nozzle height</td>
<td>1330 mm</td>
</tr>
<tr>
<td>Nozzle type and port angles</td>
<td>Bifurcated type: 52 to 35 degree step angles at the top 45 degree port angle at the bottom</td>
</tr>
<tr>
<td>Nozzle port area</td>
<td>85 mm (height) x 80 mm (width) each</td>
</tr>
<tr>
<td>Port to bore (at UTN top) area ratio</td>
<td>2.13</td>
</tr>
<tr>
<td>SEN depth</td>
<td>178 mm</td>
</tr>
<tr>
<td>Mold width</td>
<td>1300 mm</td>
</tr>
<tr>
<td>Mold thickness</td>
<td>250 mm</td>
</tr>
<tr>
<td>Domain width</td>
<td>650 mm</td>
</tr>
<tr>
<td>Domain thickness</td>
<td>250 mm</td>
</tr>
<tr>
<td>Domain length</td>
<td>3000 mm</td>
</tr>
<tr>
<td>Density (argon gas)</td>
<td>0.55 kg/m(^3) (at gas gas injection pressure (1.99e05 N/m(^2), &amp;1550°C)</td>
</tr>
<tr>
<td>Density (molten steel)</td>
<td>0.30 kg/m(^3) (at SEN depth pressure (1.13e05 N/m(^2), &amp;1550°C)</td>
</tr>
<tr>
<td>7020 kg/m(^3) (molten Steel temperature=1550°C)</td>
<td></td>
</tr>
<tr>
<td>Dynamic viscosity (argon gas)</td>
<td>7.42e-05 kg/m-s</td>
</tr>
<tr>
<td>Dynamic viscosity (molten steel)</td>
<td>0.006 kg/m-s</td>
</tr>
</tbody>
</table>
Calculation of steel velocity and pressure at gas injection

1) Steel velocity in UTN (at gas injection point)

\[ V_{s,\text{UTN}} = \frac{V_{\text{casting}} \times W_m \times t_m}{\pi (R_{\text{UTN}})^2} \]

2) Estimated Steel pressure in UTN (at gas injection point)

\[ P_{s,\text{UTN}} = P_{s,\text{tun level}} + \rho_s g h_{\text{tun level}} - \frac{1}{2} \rho_s v_{s,\text{tun level}}^2 \]

Calculation of gas flow rate at gas injection point

\[ Q_g = W_m \times t_m \times v_{\text{cast}} \]

\[ Q_{g,\text{STP}} = \frac{P_g}{P_{g,\text{STP}}} \left( \frac{273}{T} \right) \]

\[ Q_{g,\text{STP}} = \left( P_{g,\text{STP}} \right) \left( \frac{T}{273} \right) = 3.2 \]

Average argon gas % in nozzle:

\[ F_g = \frac{Q_g \times 100}{W_m \times t_m \times v_{\text{cast}} + Q_g} = 5.22\% \]
Calculation of gas velocity profile at UTN

\[ Q_g = 2\pi R_{UTN} \times \frac{3}{2} L \times v_g + 2\pi R_{UTN} \int_0^L v_g \left(1 - \frac{x}{L}\right) dx = 4\pi R_{UTN} L v_g \]

Gas flow rate of constant gas velocity part
Gas flow rate of linearly decreasing gas velocity part

We can calculate the gas velocity at injection point \( v_g \) by this equation:

\[ v_g (m/\text{sec}) = \begin{cases} 0.01928 \times (47 \text{mm} \leq x < 23.5 \text{mm}) \\ 0.01928 \left(1.5 - \frac{x}{47}\right) (23.5 \text{mm} \leq x \leq 70.5 \text{mm}) \end{cases} \]

Average gas velocity
Gas flow rate of constant gas velocity part
Gas flow rate of linearly decreasing gas velocity part

<table>
<thead>
<tr>
<th>( Q_g )</th>
<th>Gas flow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.2SLPM(273k)</td>
<td>30LPM(1823K &amp;@ injection)</td>
</tr>
<tr>
<td>55LPM (1823 @ SEN depth)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( v_g )</th>
<th>Average gas velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_g )</td>
<td>( v_g ) (lower part of injection area)</td>
</tr>
<tr>
<td>0.01928 m/s (1823 K &amp;@ injection)</td>
<td>0.036 m/s (1823 K &amp;@ SEN depth)</td>
</tr>
</tbody>
</table>

\( R_{UTN} \) | Inner radius of UTN |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>43mm</td>
<td></td>
</tr>
</tbody>
</table>

\( H \) | Distance between gas injection point and steel surface of UTN |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1725mm</td>
<td></td>
</tr>
</tbody>
</table>

\( L \) | Distance from gas injection point and UTN bottom |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>47mm</td>
<td></td>
</tr>
</tbody>
</table>

\( X \) | Distance from gas injection point (mm) |
|---|---|

Computational models (single-phase)
(Flow in combined nozzle and mold)

- Single-phase flow:
  - 3-D steady state Navier-stokes equations with mass conservation
  - RANS approach to model turbulence, k-\( \epsilon \) turbulence model was used.
  - Mass and momentum sink terms to model shell solidification were implemented using a User-Defined Function (UDF).

- VOF (volume of fluid) model for slag-steel interface:
  - VOF model has been used without any argon gas injection to track steel-slag interface.
  - Energy equation was solved in slag layer and viscosity of the slag was considered to be a function of temperature. Within steel a constant temperature of 1550 degree C was considered.
  - RANS approach with k-\( \epsilon \) turbulence model was used.
  - Mass and momentum sink terms to model shell solidification were implemented using a User-Defined Function (UDF).
Multiphase computational models (combined nozzle & mold)

- Multiphase flow:
  - Gas was injected at UTN based upon gas velocity profile shown in previous slides using a UDF.
  - This gas was removed by creating mass, and momentum sink in the cells below free surface.
  - Eulerian-Eulerian model (E-E model)
    - Two sets of governing equations for the field variables (i.e. mass, x-, y- and z- momentum equations for each phase).
    - Two-equation mixture k-ε model for turbulence
    - Schiller-Naumann drag formulation for steady phase coupling after modifying it for three-way coupling (i.e. bubble-bubble fluid dynamic interaction) using a UDF.
  - Eulerian-Mixture model (E-M model)
    - One set of governing equation for the field variables (i.e. mass, x-, y- and z-momentum equation for mixture phase).
    - Volume-fraction equation and algebraic relative velocity expression for gas phase
    - Assuming smaller response time of gas bubbles in steel, relative velocity expression was simplified to terminal velocity and after modifications with three way coupling effect was implemented using a UDF.

Mean Bubble diameter: Active sites per unit area in porous refractory for gas injection

Ref: Go Gi Lee, Seon-Hyo Kim and Brian G. Thomas, “Effect of refractory properties on initial bubble formation in continuous casting nozzles”, 2009 (In progress)

Uncoated and coated (with siloxane and silane solution) MgO refractory

Important Findings: Active sites per unit area increases with increasing argon gas injection, permeability, down-ward liquid velocity and decreasing contact angle (i.e lower sites in steel-argon system).

Motivations: Higher contact angle case of surface coating in air-water system is expected to closely imitates higher surface tension steel-argon system.
Mean bubble diameter: Steel-argon vs water-air analogy

- Water model experiments have been used to measure active sites per unit area in surface coated Mgo refractory.

- Because of the higher contact angle in steel-argon systems (~100 degree), they behave much like water-air system with surface coated porous refractory.

Mean bubble diameter: In steel-argon system predicted by H. Bai and B. G. Thomas (2001)


2.4 mm mean bubble diameter

- Analytical model was developed and verified in water-air experiments.
- Analytical model was further extended to be used to predict average bubble size in steel-argon system.
- Mean bubble diameter was found independent of injection hole size.
Mean bubble diameter: Calculations (using Bai et al.(2001) and Lee et al’s(2009) formulations)

- Gas injection flow rate per unit area(SLM/cm², considering A=πxDUTN x 2.5) = 9.2 SLM*(3.2LM/SLM)/317.45 cm² = 0.09 LM/cm²
- Average down-ward liquid velocity at gas injection in UTN = 1.52 m/s
- Permeability of MgO porous refractory 7.52 nPm
- Based upon GG Lee et al (2009), for a given gas flow rate (0.09 SLPM/cm²), permeability (7.52nPm) and downward liquid velocity (1.52 m/s), active sites per cm² = 4.7 (see fig on slide-11 for reference).
- Total active sites in porous refractory in gas exiting region = 4.7x317.45 = 1492
- Gas flow rate per pore at injection temperature and pressure=490(ml/s)/1492sites=0.32 ml/s
- Using Bai et al’s formulations, for known mean downward liquid velocity (1.52m/s) and gas flow rate per pore (0.32 ml/s), we can get mean bubble diameter = 2.4 mm (see fig in slide-13 for more details).

Various types of electo-magnetic mold flow control systems showing hardware and field shape

(a) Local EMBr (b) Ruler EMBr (c) Double ruler EMBr (d) Moving field
MHD computational flow model

- Magnetic induction method:
  - Solves an induced magnetic field transport equation
  - Induced magnetic field is used to calculate induced current and Lorentz force
  - Lorentz force is used as a source term in momentum equations
  - MHD simulations have been performed with single-phase and multiphase Eulerian-mixture model.

Measured and applied magnetic field in simulations

With FC Mold

Mold showing double magnetic field rulers

Manufactured by ABB

U:150A, L:300A  U:300A, L:300A

Magnetic field magnitude

Tesla

Measuring lines

Center

350mm 700mm

Mold (right narrow-face)
• Combined computational domain of nozzle and mold was created assuming right-left symmetry. (right half is taken) (next slide)
• 0.50 million hexa-cells were used in the computational domain to model turbulent nozzle and mold flow.
• Domain was modified based upon shell profile and sink elements (mass and momentum) of 1 mm thickness were created close to shell in the molten steel domain to incorporate the effect of shell solidification.
• In steel-argon multiphase simulations, sink elements of again 1mm thickness were created just below the free-surface to remove the argon gas which is injected at UTN.
• In VOF simulations to model the effect of steel-slag interface, a 15 mm thickness of slag was considered.
• Convergence was pursued in almost all cases until scaled residuals were reduced to $10^{-4}$. 

Combined nozzle and mold mesh (0.50 Million hexa-cells)

(a) Combine nozzle & mold
(b) Slide-gate
(c) Front view close-up at SEN outlet port
(d) Port mesh

Sink elements created to model the effect of shell-solidification
Boundary conditions

- At UTN top (i.e. tundish bottom), velocity inlet boundary condition for steel was applied as per the casting speed and correspondingly calculated flow rate.
- Bottom of mold was taken at constant pressure outlet (0 gauge Pa).
- Shell boundary was moved downward with casting speed.
- Top free-surface of the mold was taken no-slip boundary since it imitates effect of high viscosity slag on steel flow.
- In multiphase steel-argon simulations, gas was injected at UTN based upon a calculated velocity profile and given flow rate.
- In VOF simulations, top surface of the molten slag (i.e. sintered layer) was assumed no-slip at 1145 degree C. Slag (front, back, right) walls were given temperature boundary condition with temperature linearly changing from 1550 degree C to 1145 degree C. Slag touching the outer Nozzle was assumed insulated.

Various cases modeled with their labels and process parameters

<table>
<thead>
<tr>
<th>Case no</th>
<th>Case label</th>
<th>Model type</th>
<th>Magnetic field</th>
<th>Bubble size (mm)</th>
<th>Gas flow rate (LPM)</th>
<th>Bubble-bubble interaction</th>
<th>Bottom port angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NOFC_SINGLE</td>
<td>Single-phase</td>
<td>no</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>NOFC_SINGLE_35</td>
<td>Single-phase</td>
<td>no</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>150A_SINGLE</td>
<td>Single-phase</td>
<td>U:150A, L:300A</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>300A_SINGLE</td>
<td>Single-phase</td>
<td>U:300A, L:300A</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>45</td>
</tr>
<tr>
<td>5</td>
<td>NOFC_2.4_30_EM_BB</td>
<td>E-M</td>
<td>no</td>
<td>2.4</td>
<td>30</td>
<td>yes</td>
<td>45</td>
</tr>
<tr>
<td>6</td>
<td>150A_2.4_30_EM_BB</td>
<td>E-M</td>
<td>U:150A, L:300A</td>
<td>2.4</td>
<td>30</td>
<td>yes</td>
<td>45</td>
</tr>
<tr>
<td>7</td>
<td>300A_2.4_30_EM_BB</td>
<td>E-M</td>
<td>U:300A, L:300A</td>
<td>2.4</td>
<td>30</td>
<td>yes</td>
<td>45</td>
</tr>
<tr>
<td>8</td>
<td>NOFC_2.0_30_EE_NOBB</td>
<td>E-E</td>
<td>no</td>
<td>2.0</td>
<td>30</td>
<td>no</td>
<td>45</td>
</tr>
<tr>
<td>9</td>
<td>NOFC_2.4_30_EE_BB</td>
<td>E-E</td>
<td>no</td>
<td>2.4</td>
<td>30</td>
<td>yes</td>
<td>45</td>
</tr>
<tr>
<td>10</td>
<td>NOFC_2.4_55_EM_BB</td>
<td>E-M</td>
<td>no</td>
<td>2.4</td>
<td>55</td>
<td>yes</td>
<td>45</td>
</tr>
</tbody>
</table>
Single-phase steel flow in SEN (45(B):35(TB):52(TT) and 35(B):35(TB):52(TT) degree port angled nozzles) \((V_{\text{casting}}=1.64 \text{ m/min})\)

Asymmetric swirling flow at the bottom in a slide-gate SEN

Typical, double vortices at the bottom in aligned stopper rod SEN

Stronger swirling flow

Strong downward flow

Steel flow at SEN bottom and port in aligned stopper rod and slide-gate SEN (single-phase: steel flow) \((V_{\text{casting}}=1.64 \text{ m/min})\)

As expected, aligned stopper-rod gives two opposite rotating vortices compared to one in slide-gate type control.

Slide-gate gives swirling flow because of single vortex at bottom well.

Flow from stopper-rod SEN port is directed downward and therefore giving more reverse flow in the top region.
Steel velocity at ports in slide gate nozzle with 45(B):35(TB):52(TT) and 35(B):35(TB):52(TT) port angles (single-phase: steel flow) ($V_{\text{casting}} = 1.64 \text{ m/min}$)

- 45(B):35(TB):52(TT)
- 35(B):35(TB):52(TT)

>> More stagnation region at the bottom with 35(B):35(TB):52(TT) compared to 45(B):35(TB):52(TT)
>> 35(B):35(TB):52(TT) SEN being slightly more close to square gives higher swirling flow.
>> Less reverse flow on the top of port in 35(B):35(TB):52(TT) nozzle.
>> Qualitatively, both nozzles give same flow patterns at the port.

Comparison of port and bottom well velocity with and without magnetic field (single-phase: steel flow) ($V_{\text{casting}} = 1.64 \text{ m/min}$)

- No magnetic field
- U:150 A, L:300 A, magnetic field
- U:300 A, L:300 A, magnetic field

>> Magnetic field reduces swirl in the nozzle bottom thus lessens outward flow from the top left of port.
>> The suppression of swirl increases with magnetic field strength (upper ruler).
Comparison of port and SEN symmetry plane velocities in single-phase steel flow with FC on (U:300A, L:300A) and FC off conditions ($V_{\text{casting}}=1.64$ m/min)

- More flow from left upward region in FC-off case thus causing nose to jet.
- FC off shows bigger swirl at symmetry plane at the well of the SEN.

Single-phase steel and multiphase steel-argon flow comparison at the slide-gate region ($V_{\text{casting}}=1.64$ m/min)

- Argon gas does not affect high speed flow close to slide-gate.
- Eulerian-Eulerian and Eulerian-mixture models are found giving reasonably close results except showing minor differences in velocity behind slide-gate.
Effect of bubble size and b-b fluid interaction on gas collection in the nozzle (2mm and 2.4 mm bubble) (Eulerian-Eulerian model) \( (V_{\text{casting}}=1.64 \text{ m/min}) \)

>> gas gets collected in recirculation zones.


>> with larger bubbles, gas stay attached to the nozzle wall

>> volume fraction distribution at port exit is around similar except smaller size showing a smaller region at bottom left and larger size shows more spread at the top of the port.

Effect of gas flow rate on gas fraction in nozzle for 29.39 and 54.8 LPM \( (V_{\text{casting}}=1.64 \text{ m/min}) \)

>> qualitatively look similar.

>>Higher gas injection clearly shows bigger gas pockets behind slide-gate and at the top of the port.

>>Gas with higher flow rate has more spread in left top and right middle region before exiting the port to the mold.
Qualitative comparison of argon gas volume fraction on the top of port with water model measurements ($V_{\text{casting}} = 1.64$ m/min)

55LPM: E-mixture model
2.4 mm bubble

30LPM: E-E model
2 mm bubble

45(B):35(TB):52(TT) port angles

90 degree slide gate

Water model:

35(B):35(TB):52(TT) port angles

GG Lee’s (2006) (measurements)

>> Gas collection at the top of the port is consistent in all cases.

>> E-E model always shows gas collected with the swirl at the bottom of the SEN.

>> E-mixture model suggests gas exiting from top and mid of the port and does not show significant collection of gas at bottom of SEN.

>> Gas behavior looks better captured by E-mixture model.

Port velocity in E-E and E-mixture models (Multiphase flow: steel-argon) ($V_{\text{casting}} = 1.64$ m/min) (30LPM, 2.4 mm bubble)

E-E model shows stronger swirl at the bottom of the SEN.

This swirl seems to be the main cause of the bigger gas pocket in there.
Effect of gas and magnetic field on gas fraction in nozzle (30LPM gas, 2.4 mm bubble) 
(V\textsubscript{casting} = 1.64 m/min)

>> Qualitatively, E-E and E-mixture models predict around same argon gas distribution in the nozzle.

>> Magnetic field shifts gas exit slightly towards bottom.

>> Change in magnetic field (from U:150A to U:300A) does not affect argon gas distribution much.

Effect of magnetic field on port velocity (Multiphase flow Steel-argon flow), (29.39LPM, 2.4 mm bubbles) (V\textsubscript{casting} = 1.64 m/min)

>> Magnetic field slightly reduces the swirl and left top port velocity (which causes nose to jet).

>> Effect of magnetic field is small on turbulent steel-argon flow compared to single-phase steel flow.
Effect of port angle on steel flow: 
35(B):35(TB):52(TT) vs 45(B):35(TB):52(TT) port angles 
($V_{\text{casting}}=1.64$ m/min)

Current work is consistent with previous finding of jet nose

Effect of magnetic field on single-phase steel flow close to port
($V_{\text{casting}}=1.64$ m/min)

With FC-off

IR OR

-30mm +30mm

With FC-on
U:300A, L:300A

Near IR Center Near OR

No significant effect (near OR)

Effect of argon gas on steel flow close to port in mold and SEN
($V_{\text{casting}}=1.64$ m/min)

Single phase steel-flow

IR OR

-30mm +30mm

With 30LPM argon gas, 2.4 mm bubble

Center Near OR

Near IR
Steel and argon velocity close to port, FC-off \((V_{\text{casting}}=1.64 \text{ m/min})\) (30LPM, 2.4 mm bubble)

Steel and argon flow close to port, FC-on \((U:300A, L:300A)\) (30LPM, 2.4 mm bubble) \((V_{\text{casting}}=1.64 \text{ m/min})\)
Effect of magnetic field on multiphase steel-argon flow (30LPM, 2.4mm bubble) 
\( (V_{\text{casting}} = 1.64 \text{ m/min}) \)

Without field

- Liquid velocity

With field

- U:300A, L:300A

Lorentz force with and without gas
\( (V_{\text{casting}} = 1.64 \text{ m/min}) \) (U:300A, L:300A)
Single-phase steel flow in the mold ($V_{\text{casting}} = 1.64 \text{ m/min}$)

- Velocity contours
- Velocity contours & streamlines
- Complex flow pattern: Partially double roll flow
- Reason for this nose: slide gate caused swirl and expectedly affected by step angle nozzle. (52° to 36° angles on top)

Steel velocity vectors and contours while looking from right narrow face (single-phase steel flow)

- View from right narrow face with location of port shown in inset
- Port velocity magnitude (max: secondary velocity = 0.85)
- Distance from symmetry mid-plane towards right narrow face

- Jet impingement region
Velocity and kinetic energy contours with streamlines at 15 mm below surface (single-phase steel flow)

Regions of higher upward velocity

Regions of higher turbulent kinetic energy

Free surface level comparison between VOF model and pressure distribution method assuming flat no-slip top surface ($V_{\text{casting}} = 1.64 \text{ m/min}$)

>> Free surface profile is reasonably calculated by pressure distribution method (with flat interface assumption) considering the computational difficulties involved with VOF method (especially in multiphase and multiphase MHD flows)
Effect of magnetic field on single-phase steel flow (velocity contours and streamlines at mold-mid plane)  
(single-phase flow, U:300A, L:300A)

Velocity contours looking from right narrow-face towards symmetry (single-phase flow, U:300A, L:300A)

Distance from symmetry mid-plane towards right narrow face
Jet has more horizontal but less vertical spread compared to non-magnetic field case.
Induced current density and Lorentz force (single-phase flow, U:300A, L:300A)

Distance from symmetry mid-plane towards right narrow face

Current density magnitude at Port

Lorentz force magnitude at Port

Velocity and streamlines at 15 mm below surface (single-phase flow, U:300A, L:300A)

Free-surface velocity magnitude with vectors
Free-surface velocity magnitude with streamlines

Turbulent kinetic energy

>>Classic double-roll flow, i.e. steel rising up after striking narrow face and flowing in reverse direction towards SEN in plug like flow.
Velocity and streamlines at 15 mm below surface (single-phase flow, U:150A, L:300A)

Minutely lower surface velocity compared to (U:300A, L:300A) case.

Since, upper ruler is not exactly at port and moreover has weak strength close to narrow face, it does not have much effect on surface velocity.

Field strength of lower ruler in jet region has more effect on surface velocity.

Eulerian-Mixture model with terminal velocity formulation (30LPM, 2.4 mm bubble size)

Top-view 15 mm below free-surface
Two-Fluid model (i.e. Eulerian-Eulerian model) (30LPM, 2.4 mm bubble size)

Argon volume fraction with streamlines

Steel velocity magnitude with vectors

Mixture Turbulent kinetic energy

Argon velocity vectors and magnitude

Comparison of mold-mid plane velocity contours and streamlines (E-E and E-M models) (30LPM, 2.4 mm bubble size)

Eulerian-Eulerian model

Eulerian-mixture model

Velocity contours & streamlines
Discussions on comparison of Eulerian-Eulerian and Eulerian-mixture model

- Eulerian-Eulerian model (Two-Fluid model) is the most accurate and versatile multiphase model. Model is stable and applicable over whole range (0-1) of gas volume fraction.
- Unfortunately, FLUENT does not have MHD model implemented in Eulerian-Eulerian model and has it only with Eulerian-mixture model therefore we are bound to use Eulerian-mixture model.
- Eulerian-mixture model becomes less and less applicable at higher volume fractions and therefore as gas volume fraction increases in stagnation regions (like behind slide-gate, on the top of port etc) conventional slip velocity formulation (algebraic slip or terminal velocity) blows up and solution never converges. Reason for this is constant high gas velocity with slip formulation and mixture continuity equation becoming more dependent on gas mass.
- In order to avoid stability problems, three-way coupling correction (Richardson-Zaki power equation, bubble-bubble fluid dynamic interaction) has been implemented in drag formulation of Eulerian-Eulerian and slip velocity formulation of Eulerian-mixture models.
- After the implementation of this correction, Eulerian-mixture model behaved nicely and the results of the two models matched closely. Minute changes in the results of Eulerian-Eulerian model are seen with the implementation of this correction.
- Argon gas is found to be following steel closely in Eulerian-mixture model as per expectations.

Steel and argon velocity contours & vectors with Argon gas volume fraction, (30LPM, 2.4 mm bubble) (E-M model)

- Gas rising from port top, Upward flow
- Gas exit region: consistent with steel swirl flow

View from right narrow-face
Steel and argon gas velocity vectors & contours (30 LPM, 2.4 mm bubble) (E-M model)

Liquid velocity, 15 mm below free surface

Liquid velocity in the top region

Gas velocity, 15 mm below free surface

Argon volume fraction contours with argon velocity vectors (30LPM, 2.4 mm bubble) (E-M model)

NOTE: three figures have the difference of contour color bar range

Contours of argon gas volume fraction with velocity vectors at mold mid-plane

Front-view
Argon volume fraction contours with argon velocity vectors (55LPM, 2.4 mm bubble) (E-M model)

Higher gas flow rate, 54.8 LPM

comparison of argon gas volume fraction at 15 mm below free surface in 30LPM and 55LPM gas flow rates (2.4 mm bubble) (E-M model)

Higher gas flow rates shows more spread of gas on the top surface with lower fraction following steel velocity wave closely and thus causing more asymmetry in gas fraction.
Streamlines and velocity contours of steel flow at mold mid-plane
(30LPM, 2.0 mm bubble) (E-E model without bb interaction
correction)

Argon gas void fractions

Gas trajectories, gas volume fraction contours and velocity
distributors at the mid-plane in the mold (30LPM, 2.0 mm bubble)
(E-E model without bb interaction correction)
Steel and argon gas velocity vectors and volume fraction contours at the right port exit (30LPM, 2.0 mm bubble) (E-E model without bb interaction correction)

Combine effect of buoyancy, vortex (collecting gas at the top of the port) and forward steel velocity

Argon gas volume fraction at port exit

Steel velocity contours

Effect of gas pocket at the bottom of the nozzle and forward steel velocity

Argon gas velocity vectors at port exit

Steel and argon gas velocity, argon velocity and fraction at 15 mm below surface (30LPM, 2.0 mm bubble) (E-E model without bb interaction correction)

Gas exit regions

Steel velocity contours and vectors at free surface

Argon gas volume fraction

>> Argon gas spread more on the top surface in case of smaller diameter.
Strong Mag Field: Steel and argon velocity contours & vectors with Argon gas volume fraction (30LPM, 2.4 mm bubble size, E-M) (U:300A, L:300A)

Gas rising from top of port
Gas exit region: consistent with steel swirl flow
Gas exit region shifted downward

Mixture/steel velocity magnitude with secondary flow vectors
Argon gas velocity magnitude with secondary gas flow vectors
Argon gas volume fraction with secondary gas flow vectors

View from right narrow-face

Steel-argon multiphase flow (30 LPM, 2.4 mm bubble size) (U:300A, L:300A) (E-M model)

Liquid velocity 15mm below surface
Liquid velocity in the top region
Gas exit region

Gas velocity at 15 mm below surface

University of Illinois at Urbana-Champaign • Metals Processing Simulation Lab • R Chaudhary • 65
Gas velocity vectors and volume fraction contours (30LPM, 2.4 mm bubble size) (U:300A, L:300A) (E-M model)

Effect of Magnetic Field:
(compare steel velocity at mold mid plane and at 15 mm from top surface) (30 LPM, 2.4 mm bubble) (E-M model) (U:300A, L:300A)
Effect of Magnetic Field:
(compare argon gas velocity at mold mid plane and at 15 mm from top surface) (30 LPM, 2.4 mm bubble) (E-M model)
(U:300A, L:300A)

Effect of Magnetic Field:
(compare gas fractions 15 mm from top surface) (30 LPM, 2.4 mm bubble) (E-M model)

Without Field

With Field
(U:300A, L:300A)

>> FC on reduces gas spread towards narrow face.
>> FC on shifts gas exit regions towards OR close to SEN.

Gas: 29.39 LPM
Effect of magnetic field on surface level along the mid-line between wide faces

>> Close to SEN, gas gives higher surface wave.
>> Magnetic field suppresses the rising velocity of gas close to SEN and therefore indirectly reducing the surface level.

Discussion on effect of magnetic field on steel-argon multiphase flow

- Steel and argon flow on the surface perpendicular (horizontal & vertical) to magnetic field is reduced in FC on case.
- Magnetic field suppresses nose to the jet. (consistent with single-phase steel flow)
- Magnetic field has no effect on velocity parallel to field.
- Magnetic field reduces vertical gas velocity.
- Lower field ruler bends jet slightly upward causing higher upward velocity in FC on compared to FC off.
- Upper ruler pushes this upward flow towards SEN horizontally and thus forcing this to move towards SEN along with gas.
- Gas exits from OR side close to SEN.
Flow patterns with FC-off

1. Flow is transient
2. Close to double-roll

Flow pattern variation with FC on

1. Flow is transient
< Dominant flow pattern considering horizontal velocity >

Flow is more uniform toward SEN with FC on
Less cross-flow from outside to inside with FC on

Comparison of surface-velocity predictions with nail board measurements (FC-off)

Note: Vectors are anchored at the center position.
Comparison of surface velocity (magnitude) predictions with nail-board measurements

Meniscus level profile (at left narrow face)
**Test3(most recent): Influence of FC on Surface Flow Pattern**

**FC OFF**

![Flow pattern diagram](outside inside)

**FC ON**

![Flow pattern diagram](outside inside)

Total 6 cases: means are shown here

Measurements suggest double-roll flow.

---

**Differences between current work (Chaudhary R, Cho S-M and Lee Go-Gi (2008-2009)) and Lee et al’s(2006) previous work**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Previous work (Go Gi, 2006)</th>
<th>Current work (simulations) (Cho S-M &amp; Lee Go Gi, measured, 2008&amp; 2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting speed</td>
<td>1.46 m/min</td>
<td>1.64 m/min</td>
</tr>
<tr>
<td>Slab width</td>
<td>1570 mm</td>
<td>1300 mm</td>
</tr>
<tr>
<td>Slab thickness</td>
<td>230 mm</td>
<td>250 mm</td>
</tr>
<tr>
<td>Gas injection</td>
<td>9.6 SLPM</td>
<td>9.2 SLPM</td>
</tr>
<tr>
<td>Mean bubble diameter</td>
<td>2.3 mm (simulation)</td>
<td>(2.0/2.4 mm in current simulations)</td>
</tr>
<tr>
<td>Port angles (step angle)</td>
<td>52, 35 degree (top)</td>
<td>52, 35 degree (top)</td>
</tr>
<tr>
<td></td>
<td>35 degree (bottom)</td>
<td>45 degree (bottom)</td>
</tr>
<tr>
<td>Nozzle details</td>
<td>90 degree slide-gate, bifurcated type</td>
<td>90 degree slide-gate, bifurcated type</td>
</tr>
<tr>
<td>Nozzle port height x width</td>
<td>98mm x 70mm</td>
<td>85mm x 80mm</td>
</tr>
<tr>
<td>Nozzle bore diameter</td>
<td>75 mm (constant)</td>
<td>91mm(top)-80mm (bottom)</td>
</tr>
<tr>
<td>SEN depth</td>
<td>180mm</td>
<td>178mm</td>
</tr>
<tr>
<td>Shell</td>
<td>No shell in the model.</td>
<td>Shell incorporated in the model.</td>
</tr>
</tbody>
</table>

Practically, current work is quite similar to GG Lee et al’s (2006) work except minor differences mentioned above.

I expect these two works should match qualitatively???
Lee et al (2006) simulation work (results after 30 secs)

- Generally double-roll flow pattern, impinging on NF;
- Some flow up outside wide face, across top surface, and down inside wide face;
- Results match plant measurements.

Is this really double roll flow?????? I think not!!

Lagrangian gas bubble simulations for 4 secs (Lee et al(2006))

>>>4 sec not enough for steady state

>>> gas exits from OR side of the free surface (consistent with current simulation findings)
GG Lee et al (2006) free surface level and nailboard velocity measurements

Increasing gas flow rate
- Changes flow pattern
- Asymmetric flow across the top surface

Comparison of current simulations with GG Lee (2006) measurements

Gas exit regions

Max: 0.16 m/s
Simulated port velocities and gas bubble concentration (Lee et al(2006))

- Stronger steel flow from bottom right (of right nozzle port)
- More gas exits top right
- Higher gas flow rate causes stronger asymmetric recirculation flow at nozzle outlet port

I do not agree with this claim, asymmetric recirculation flow is mainly caused by slide-gate and gas is found to have very small effect on it. Moreover, it is difficult to claim this based upon 30 sec real time simulations. As I found gas follows the nozzle swirl and exits port from left top then right top as claimed by Go Gi.

>>>Port velocities showing swirling flow are consistent with current work.

Summary

- 3-D, steady, steel single-phase and steel-argon multiphase MHD flow simulations were performed on a slide gate type flow control nozzle and mold.
- In all flow simulations, mold was modified based up on solidified shell profile and sink terms were added to model the effect of shell solidification.
- In multiphase steel-argon flows, argon gas was injected based upon calculated gas velocity profile above UTN.
- This injected gas was removed by creating sink elements just below free surface.
- Constant mean bubble diameter calculated based upon GG Lee and Bai et al’s work (=2.4 mm) was considered in modeling.
- Eulerian-Eulerian and Eulerian-mixture model are found matching nicely with the three-way coupling effects (bubble-bubble fluid dynamic effects). Based upon this outcome, Eulerian-mixture model augmented with bubble-bubble fluid dynamic interaction correction is used for multiphase simulations (i.e. with and without magnetic field).
Conclusions on single-phase steel flow

- Slide gate causes swirl in the nozzle bottom and therefore jet gives higher velocity at the bottom right of the port directed towards inner radius. With stopper rod type SEN, flow shows front and back symmetry with more flow coming out from nozzle bottom.
- Slide gate also causes nose to the jet with the swirl. With the nose and steeper jet, flow is directed downward and jet looses momentum faster and thus giving weak upward reverse surface flow towards SEN after hitting narrow face. Reporting of nose in the jet is consistent with the findings of Thomas et al (1999) in 90 degree slide-gate nozzle.
- This weak upward flow in the upper roll from narrow face to SEN fights upward flow from around jet close to SEN and ends up causing two rolls in the upper region. (partially double-roll flow)
- Port with 35(B):35(TB):52(TT) angles showed stronger swirling flow with more stagnation region at the bottom of the SEN well and smaller reverse flow zone at the top of the port.
- With magnetic field, upper magnetic ruler kills nose and lower ruler bends the jet towards upward and thus promoting classic double roll flow.

Conclusions on Multiphase flow (steel-argon flow)

- Argon gas collects in stagnation regions behind slide-gate, and on the top of port. More gas exits from the top of the port thus buoyancy effect are evident.
- Argon gas has minor effects on high speed steel flow in the nozzle. E-E and E-M models match nicely except behind the slide-gate where gas collects.
- In mold, maximum gas comes out from OR side close to SEN. As expected, buoyancy force is high in steel-argon system which forces gas to leave mold domain through the shortest path. Remaining gas flows with steel momentum because of drag force towards OR and exit mold mid-way the SEN and narrow face towards OR. On the top surface, mixture/steel flow is directed away from the gas exit regions (mostly from OR side towards IR). This finding is consistent with Go Gi’s (2006) measurements and simulations on step-angle slide gate nozzle.
Conclusions on effect of magnetic field on multiphase steel-argon flow

- With magnetic field, more gas exits closer to SEN towards OR due to decelerating effects of Lorentz force on the jet.

Discussion on experimental validation

- Since, GG Lee et al’s (2006) work on steel-argon flow is quite similar to the current multiphase work and as per expectations, these two are qualitatively matching.
- Possible reasons of non-matching with current measurements:
  - Multiphase flow model trouble (need more than 1 bubble diameter)
  - K-ε turbulence modeling limitations/transient flow
  - Leaking gas (injected 9.2 SLM, in steel ??)
  - Clogging (focused jet: better penetration, different velocities right and left)
  - Flow misalignment
- Suggestions???
Acknowledgements

- Continuous Casting Consortium Members (ABB, Arcelor-Mittal, Baosteel, Corus, Delavan/Goodrich, LWB Refractories, Nucor, Nippon Steel, Postech, Steel Dynamics, ANSYS-Fluent)
- National Center for Supercomputing Applications (NCSA) at UIUC
- Hyun Na Bae, Hyoung Jun Lee from POSTECH, South Korea.
- Lance Hibbeler, Varun Singh and Other Graduate students at Metal Processing Lab.