Transient Turbulent Multiphase Flow and Level Fluctuation Defects in Slab Casting


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University of Illinois at Urbana-Champaign

**Global R&D at Hamilton
ArcelorMittal Dofasco Inc.

OUTLINE

- Modeling SEN flow rate using two models: stopper-based model and level-based model, to provide inlet boundary conditions for the transient simulations
- Multiphase Flow Computational Model Validation via comparison with water model measured data
- Turbulent multiphase flow simulation of steel flow in SEN and mold in No. 1 CC caster of Dofasco, using RANS and LES models
- Future work
Modeling SEN Flow Rate – Objectives

• to provide accurate inlet boundary conditions for the CFD transient simulations, since:
  – SEN flow rate cannot be accurately measured, especially for cases with sudden changes of the stopper rod position, thus needs modeling;
  – SEN flow rate change with time as inlet boundary condition is crucial to the accuracy of the transient CFD simulations

• to study clogging during casting process
  – since clogging cannot be measured directly, but is critical to the flow patterns in the mold and the quality of the final products
  – by comparing flow rates from zero-clogging model prediction with the plant trial measurements

Two Models to Predict SEN Flow Rate

• Stopper-based Model
  – using stopper-rod position to predict the flow rate in SEN
  – based on the analysis of Bernoulli’s equation
  – parameters including:
    • measured stopper rod position
    • stopper rod zero-flow position
    • tundish fraction

• Level-based Model
  – using measured mold level signal and casting speed to predict the flow rate in SEN
  – based on the mass balance at SEN inlet, mold bottom and mold level
  – parameters including:
    • measured mold level
    • measured casting speed
Stopper-based SEN Flow Rate Model

--- Analysis of Bernoulli’s Equation

**Bernoulli’s Equation:**

\[
\frac{p_1}{\rho g} + \frac{V_1^2}{2g} = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + h_{\text{minor}} + h_{\text{friction}} + h_{\text{clogging}}
\]

At location 1 at tundish meniscus:

\[
p_1 = 1 \text{ atm}; \quad V_1 = 0 \text{ m/s};
\]

At location 2 at port exit:

\[
p_2 = 1 \text{ atm} \quad \rho g h_{\text{sen,sub}} \quad V_2 = V_{\text{SEN}}
\]

\[
\frac{p_1 - p_2}{\rho g} + \frac{V_1^2}{2g} + \frac{V_2^2}{2g} + h_{\text{minor}} + h_{\text{friction}} + h_{\text{clogging}} = \frac{h_{\text{SEN}}}{2g} + h_{\text{minor}} + h_{\text{friction}} + h_{\text{clogging}}
\]

\[
-h_{\text{sen,sub}} + f_{\text{tundish}} h_{\text{tundish}} + L_{\text{sen}} = \frac{V_{\text{SEN}}^2}{2g} + h_{\text{minor}} + h_{\text{friction}} + h_{\text{clogging}}
\]

<table>
<thead>
<tr>
<th>Variables in the EQN</th>
<th>Physical Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_{\text{sen,sub}} )</td>
<td>SEN submergence depth</td>
</tr>
<tr>
<td>( f_{\text{tundish}} )</td>
<td>Tundish (weight) fraction</td>
</tr>
<tr>
<td>( h_{\text{tundish}} )</td>
<td>Total height of the tundish</td>
</tr>
<tr>
<td>( L_{\text{sen}} )</td>
<td>Distance from tundish bottom to SEN port center</td>
</tr>
</tbody>
</table>

**NOTE:** Minor loss at SEN port exit is ignored in the model.
Bernoulli’s Equation gives:
\[
\frac{V_{\text{SEN}}^2}{2g} + h_{\text{minor}} + h_{\text{friction}} + h_{\text{clogging}} = (L_{\text{SEN}} - h_{\text{SEN,sub}} + f_{\text{tundish}}h_{\text{tundish}})
\]

Sub-model 1 for friction head loss:
\[
h_{\text{friction}} = \xi_1 \frac{V_{\text{SEN}}^2}{2g}
\]
\(\xi_1\) : function of Re number, and SEN surface roughness, SEN diameter and SEN length

Sub-model 2 for Stopper Rod Gap Head loss:
\[
h_{\text{gap}} = \xi_2 \frac{V_{\text{SEN}}^2}{2g}
\]
\(\xi_2\) : function of stopper rod opening, SEN inner cross-section area

Sub-model 3 for Stopper Rod Gap Head loss:
\[
h_{\text{clogging}} = \xi_3 \frac{V_{\text{SEN}}^2}{2g}
\]
\(\xi_3\) : can only be estimated by comparing predicted SEN flow rate with estimated SEN flow rate from plant trials

Sub-Model 1 – Modeling Friction Head Loss

Original Bernoulli’s equation:
\[
\frac{V_{\text{SEN}}^2}{2g} + h_{\text{gap}} + h_{\text{friction}} + h_{\text{clogging}} = -h_{\text{SEN,sub}} + f_{\text{tundish}}h_{\text{tundish}} + L_{\text{SEN}}
\]

The friction head loss along the nozzle is modeled as:
\[
h_{\text{friction}} = C_1 \frac{L_{\text{SEN}} V_{\text{SEN}}^2}{D_{\text{SEN}} g}
\]
\(C_1\) is a function of Re if SEN length and diameter are fixed

Since:
1. Flow in the SEN usually reaches the Re of \(10^3\);
2. The SEN inner surface is not smooth (due to attachment of the alumina oxide inclusions)

\(C_1 = 0.07 \sim 0.08\)
Sub-Model 2 –
Modeling Stopper Rod Gap Minor Loss

Minor Loss in Contraction Case (reference [1]), from location 1 to location 2:

\[ h_{1 \rightarrow 2} = \frac{V_2^2}{2g} \frac{A_2}{A_1} \rightarrow 0 \implies \xi_{1 \rightarrow 2} = 0.5 \]

Minor Loss in Expansion Case (reference [1]), from location 2 to location 3:

\[ A_2 V_2 = A_3 V_3 \quad h_{2 \rightarrow 3} = \frac{V_3^2}{2g} \frac{A_3}{A_2} \xi_{2 \rightarrow 3} = \left( \frac{A_2}{A_3} - 1 \right)^2 \]

Assume:

\[ A_2 = C_2 h_{SRO}^2 \]

Reference [1]:

Final Form of SEN Flow Rate \( Q_{SEN} \)
from Stopper-based Model

According to the friction head loss and loss models:

\[
\frac{V_{SEN}^2}{2g} + h_{\text{gap}} + h_{\text{friction}} + h_{\text{clogging}} = -h_{\text{sen}_\text{sub}} + f_{\text{tundish}} h_{\text{tundish}} + L_{\text{SEN}}
\]

\[
\frac{V_{SEN}^2}{2g} \left[1 + 0.5 \left( A_{\text{SEN}} \frac{C_{2} h_{SRO}^2}{A_2} \right)^2 + \left( A_{\text{SEN}} \frac{C_{2} h_{SRO}^2}{A_2} - 1 \right)^2 + C_1 \frac{L_{\text{SEN}}}{D_{\text{SEN}}} \right] = -h_{\text{clogging}} = -h_{\text{sen}_\text{sub}} + f_{\text{tundish}} h_{\text{tundish}} + L_{\text{SEN}}
\]

Let \( h_{\text{clogging}} = C_3 \frac{V_{SEN}^2}{2g} \)

\[
\frac{V_{SEN}^2}{2g} \left[1 + 0.5 \left( A_{\text{SEN}} \frac{C_{2} h_{SRO}^2}{A_2} \right)^2 + \left( A_{\text{SEN}} \frac{C_{2} h_{SRO}^2}{A_2} - 1 \right)^2 + C_1 \frac{L_{\text{SEN}}}{D_{\text{SEN}}} + C_3 \right] = -h_{\text{sen}_\text{sub}} + f_{\text{tundish}} h_{\text{tundish}} + L_{\text{SEN}}
\]

\[
V_{SEN} = \sqrt{\frac{2g \left( -h_{\text{sen}_\text{sub}} + f_{\text{tundish}} h_{\text{tundish}} + L_{\text{SEN}} \right)}{1 + 0.5 \left( A_{\text{SEN}} \frac{C_{2} h_{SRO}^2}{A_2} \right)^2 + \left( A_{\text{SEN}} \frac{C_{2} h_{SRO}^2}{A_2} - 1 \right)^2 + C_1 \frac{L_{\text{SEN}}}{D_{\text{SEN}}} + C_3}}
\]

The model consists of three parameters,
\( C_1 \) for friction loss along the nozzle
\( C_2 \) for minor loss at stopper rod gap
\( C_3 \) for head loss due to clogging in the SEN

\[ Q_{SEN} = A_{\text{SEN}} \sqrt{\frac{2g \left( -h_{\text{sen}_\text{sub}} + f_{\text{tundish}} h_{\text{tundish}} + L_{\text{SEN}} \right)}{1 + 0.5 \left( A_{\text{SEN}} \frac{C_{2} h_{SRO}^2}{A_2} \right)^2 + \left( A_{\text{SEN}} \frac{C_{2} h_{SRO}^2}{A_2} - 1 \right)^2 + C_1 \frac{L_{\text{SEN}}}{D_{\text{SEN}}} + C_3}} \]
Model Parameters Calibration –1

In the final model, the parameters include $C_1$, $C_2$, and $C_3$:

$$Q_{SEN} = A_{SEN} \frac{2g (-h_{sen_sub} + f_{tundish} h_{tundish} + L_{SEN})}{\sqrt{1 + 0.5 \left( \frac{A_{SEN}}{C_2 h_{SRO}^2} \right)^2 + \left( \frac{A_{SEN}}{C_2 h_{SRO}^2} - 1 \right)^2 + C_1 \frac{L_{SEN}}{D_{SEN}} + C_3}}$$

1. As mentioned previously, according to Moody's chart, $C_1 = 0.07 \sim 0.08$
2. $C_2$ can be calibrated using the measured Throughput vs. Stopper Rod Opening data, as shown in latter slides;
3. **No Clogging Assumption**
   $C_3$ is assumed to be zero for the data used to calibrate the parameters (provided by Dofasco);

<table>
<thead>
<tr>
<th>Variables</th>
<th>Definition and Value</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$h_{sen_sub}$</td>
<td>SEN submergence depth (e.g. 0.166 m)</td>
<td>$L_{sen}$</td>
<td>Length from tudish bottom to SEN port upper edge: (e.g. 1.159 m)</td>
</tr>
<tr>
<td>$f_{tundish}$</td>
<td>Tundish (weight) fraction 0~1 (e.g. 0.8)</td>
<td>$D_{SEN}$</td>
<td>SEN inner diameter (e.g. 0.075 m)</td>
</tr>
<tr>
<td>$h_{tundish}$</td>
<td>Total height of the tundish (e.g. 1.451 m)</td>
<td>$A_{SEN}$</td>
<td>SEN inner cross-section area (e.g. 0.0044 m$^2$)</td>
</tr>
</tbody>
</table>

Model Parameters Calibration –2

Since the tundish fraction influences the pressure head in the system, in order to calibrate the model using the measured data, an estimation of the tundish fraction is needed:

During the process, it is observed that the average tundish fraction stays around 0.8, the calibration will take the following parameters:

<table>
<thead>
<tr>
<th>Variables</th>
<th>Physical Meaning</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>Friction Loss Coefficient</td>
<td>0.075</td>
</tr>
<tr>
<td>$C_3$</td>
<td>Minor Loss Coefficient due to Clogging</td>
<td>0</td>
</tr>
<tr>
<td>$f_{tundish}$</td>
<td>Tundish (weight) fraction</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Stopper-based Model
Prediction vs. Measured Data--Effect of $C_2$

- Increase of the $C_2$ coefficient leads to an upper-shift of the Stopper Rod Opening vs. Throughput curve;

(shifting curve)

- Measured data points above the blue curve indicate extra head loss from the measurement (maybe due to clogging)

Choose the Stopper Rod gap minor loss coefficient $C_2$ as 2.7 in following slides

Influence of Tundish Fraction on SEN Flow Rate

By keeping $C_2$ at 2.7 and $C_1$ at 0.075 as mentioned on last slide, varying tundish fraction from 0.2 to 0.8 at an interval of 0.2, the influence of the tundish fraction on the SEN flow rate gives:

- Increase of the tundish fraction leads to an lower-shift of the Stopper Rod Opening vs. Throughput curve;

(shifting curve)

- For most processes, the tundish fraction keeps between 0.4~0.8, varying from the blue line to the pink line in the plot
Influence of $C_1$ on SEN Flow Rate

By keeping $C_2$ at 2.7 and tundish fraction at 0.8, varying friction factor $C_1$ from 0.02 to 0.08 at an interval of 0.2, the influence of the friction factor on the SEN flow rate gives:

- Little influence is found if the throughput is less than 3.5 ton/min;

- For throughput larger than 3.5 ton/min, increase of the friction factor shifts the stopper rod opening vs. throughput curve upper. (changing curve slope)

Influence of $C_3$ on SEN Flow Rate

By keeping $C_2$ at 2.7 and tundish fraction at 0.8, friction factor $C_1$ at 0.075, the influence of the minor loss coefficient due to clogging on the SEN flow rate gives:

- For throughput larger than 2.5 ton/min, increase of the clogging minor loss coefficient shifts the stopper rod opening vs. throughput curve upper. (changing curve slope)
Level-based SEN Flow Rate Model

Flow rate based on measured casting speed:

\[ Q_m(i) = V_{\text{cast}}(i) \times W \times T \]

\( V_{\text{cast}} \) is casting speed

SEN Flow rate based on mass conservation from the mold-level signal:

\[ Q_E(i) = \frac{h_m(i+1) - h_m(i-1)}{2\Delta t} \left( W \times T - \frac{\pi d_{\text{SEn, outer}}^2}{4} \right) + Q_m(i) \]

\( h_m \) is measured mold level

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Physical Meaning</th>
<th>Parameters</th>
<th>Physical Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_m )</td>
<td>mold level</td>
<td>( d_{\text{SEn, outer}} )</td>
<td>outer diameter of SEN</td>
</tr>
<tr>
<td>( W )</td>
<td>mold width</td>
<td>( Q_E )</td>
<td>SEN flow rate prediction</td>
</tr>
<tr>
<td>( T )</td>
<td>mold thickness</td>
<td>( Q_m )</td>
<td>Throughput from measured casting speed</td>
</tr>
<tr>
<td>( \Delta t )</td>
<td>time interval between data points</td>
<td>( i )</td>
<td>( i ) th time step</td>
</tr>
</tbody>
</table>

Measured Data for Example Transient Case
-- Heat 296078, segments 1~4

Symbols represent the data recorded by the PI system,
Curves are generated by Cubic Spline Interpolation (to smoothe the data points)
Model Parameters Change during Clog Releasing

- Sudden reduction of clogging results in a decrease of the clogging head loss coefficient in the model.
- Reduction of clogging around stopper-rod tip will increase the stopper rod gap area, thus increase the gap coefficient.

Stopper-based vs. Level-based SEN Flow Rate Model
-- $C_3$ decreasing, $C_2$ increasing, $h_{SRC} = 46$ mm

- “translation of estimated SEN flow rate” curve is translated from the “estimated SEN flow rate” curve by 1.2 sec ahead
- 1.2 sec is the response time for the meniscus from observation

Stopper rod starting position: 46 mm

- $C_1 = 0.075$
- $C_2$: increasing from 1.8 to 2.2
- $C_3$: decreasing from 16 to 10
Conclusions (for part 1)

• The model predictions (from stopper-based model) are compared with measurement from Dofasco. Reasonable match is achieved.

• Three parameters in the model are calibrated to match with the measured data:
  • Friction loss coefficient varies from 0.07~0.08
  • Stopper rod gap minor loss coefficient is calibrated between 2.0~2.7
  • The clogging minor loss coefficient is assumed 0 in the calibration

Conclusions (for part 1)

• Influences of the three coefficients on the SEN flow rate is studied:
  • Increase of either the stopper rod gap minor loss coefficient $C_2$ or the tundish fraction will shift the stopper rod vs. throughput curve lower
  • Increase of either the friction loss coefficient $C_1$ or the clogging loss coefficient $C_3$ will increase the slope of the curve

• This calibrated and validated model can be used to predict clogging in the system by calibrating the clogging minor loss coefficient $C_3$ according to the measurement
Model Validation by 1:2.23 Water Model

- Objective: to validate current computational models with the water model measurement

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water flow rate</td>
<td>4.32 m³/h</td>
</tr>
<tr>
<td>Air gas injection rate</td>
<td>CASE 1: 0 LPM</td>
</tr>
<tr>
<td></td>
<td>CASE 2: 6.7 LPM (room temperature)</td>
</tr>
<tr>
<td>Nozzle submerging depth</td>
<td>76 mm</td>
</tr>
<tr>
<td>Nozzle inner diameter</td>
<td>33.6 mm</td>
</tr>
<tr>
<td>Mold width</td>
<td>717 mm</td>
</tr>
<tr>
<td>Mold thickness</td>
<td>100 mm</td>
</tr>
<tr>
<td>Domain width</td>
<td>358.5 mm</td>
</tr>
<tr>
<td>Domain thickness</td>
<td>50 mm</td>
</tr>
<tr>
<td>Domain length</td>
<td>700 mm</td>
</tr>
<tr>
<td>Density (air)</td>
<td>1.225 kg/m³ (at velocity inlet)</td>
</tr>
<tr>
<td>Density (water)</td>
<td>998.2 kg/m³</td>
</tr>
<tr>
<td>Dynamic viscosity (air)</td>
<td>1.7894e-05 kg/m-s</td>
</tr>
<tr>
<td>Dynamic viscosity (water)</td>
<td>0.001 kg/m-s</td>
</tr>
<tr>
<td>Bubble Diameter (mm)</td>
<td>2.7 mm</td>
</tr>
</tbody>
</table>

Geometry and Mesh for 1:2.23 Water Model

Total: 0.3 million structured hexahedral cells
Computational Details and Boundary Conditions

### Computational Details and B.C. Settings:

<table>
<thead>
<tr>
<th>Models and Schemes</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulence Models</td>
<td>k-epsilon with std. wall function</td>
</tr>
<tr>
<td>Multiphase Model</td>
<td>Mixture Model</td>
</tr>
<tr>
<td>Model for Shell Growth</td>
<td>No</td>
</tr>
<tr>
<td>Gas Escaping from Meniscus</td>
<td>Mass Sink for Argon Phase</td>
</tr>
<tr>
<td>Advection Discretization</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; order upwinding for k-epsilon model</td>
</tr>
<tr>
<td>Pressure Discretization</td>
<td>Body Force Weighted Scheme</td>
</tr>
</tbody>
</table>

### Parameters for the transient run:

- **Time marching scheme**: 1<sup>st</sup> order implicit, 0.05 sec time step
- **Time before collecting statistics**: 60 sec
- **Time for the stats**: 60 sec

<table>
<thead>
<tr>
<th>Domain Boundaries</th>
<th>B.C.</th>
<th>Domain Boundaries</th>
<th>B.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meniscus</td>
<td>Free-Slip Wall (no slag layer)</td>
<td>Outlet</td>
<td>Pressure Outlet</td>
</tr>
</tbody>
</table>

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### Single Phase Flow – Water Velocity Distribution

![Image of water velocity distribution](image-url)
Water Velocity Distribution at SEN Port Exit

Horizontal Velocity along Meniscus Centerline
(Prediction vs. Measurement)

Jet swirling at port corner

Back Flow Region

Port Centerline

Rui Liu

Estimate Fluctuations from calculated turbulent kinetic energy:

\[ k = \frac{1}{2} (u'^2 + v'^2 + w'^2) \quad \Rightarrow \quad |u'| \approx \sqrt{\frac{2}{3}} k \]
Water-Air Two-Phase Flow – Water Velocity Distribution

Water velocity field at center plane between wide faces

velocity magnitude (m/s)

-0.9 Mold Thickness (m)

0.66 0.84 1.03 1.21 1.40

-0.1 Mold Height (m)

-0.35 0.5 0.7 0.9

0.2 m/s

0.1 Mold Width (m)

-0.3 0.1 0.3

velocity magnitude (m/s)

1.1 1.3 1.5 1.7 1.9

Water Velocity Distribution – at SEN Port Exit

port center line

velocity magnitude (m/s)

0.5 m/s

Streamline showing jet swirling at port corner

Port Height (m)

-0.35 0.35 0.37 0.39 0.41

-0.34 0.34

Port Width (m)

-0.01 0 0.01
Water-Air Two Phase Flow – Air Velocity Distribution

3-D view of air volume fraction Iso-surface

-0.5 to 0.5 m/s

Air Volume Fraction

-0.5 to 0.5 m/s

Air Velocity Distribution – at SEN Port Exit

Port center line

-0.35 to 0.35 m/s

Air Volume Fraction

-0.35 to 0.35 m/s

Port Height (m)

Port Width (m)
Simulation VS. Measurement – Water Velocity at Meniscus Centerline

60 sec time-averaged velocity
(RMS of the mean velocity is negligible, 10^{-4} m/s magnitude)

Estimate Fluctuations from calculated turbulent kinetic energy:
\[ k = \frac{1}{2} (\mu'^2 + v'^2 + w'^2) \Rightarrow |\mu'| = \frac{2}{\sqrt{3}} k \]

Single Phase VS. Multiphase Flow – Water Velocity Distribution

- Exiting of gas at SEN port exerts a drag force acting on the liquid pointing towards meniscus, which will change the double-roll flow pattern into complex or even single-roll flow pattern, depending on the liquid/gas flow rate, mold width and bubble size distribution.
Conclusions (for part 2)

• By comparing simulation results with water model measurements,
  – for single phase flow as well as the multiphase flow with relatively low gas volume fraction (8% gas), current model is able to match nicely with experiment data
  – gas injection into the mold tends to make more “single-roll” of the flow pattern, depending on the liquid/gas flow rate
  – simulation results give lower RMS of velocities than measurements, due to:
    – use of URANS (model is diffusive)
    – use of 1\textsuperscript{st} order upwinding for advection terms (diffusive scheme)
    – use of quarter mold as domain (suppressing the bias flow between left and right part of the mold)

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3\textsuperscript{rd} PART: Computational Model Validation

Simulation of Dofasco No. 1 Steel Caster

-- Heat 296078, Time 9955 sec

Geometry and Mesh:

- blocks for structured grid meshing

<table>
<thead>
<tr>
<th>Model Geometry Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold Width</td>
<td>1.472</td>
</tr>
<tr>
<td>Domain Length</td>
<td>3.0</td>
</tr>
<tr>
<td>Mold Thickness at Meniscus</td>
<td>0.225</td>
</tr>
<tr>
<td>SEN Outer/Inner Diameter</td>
<td>0.130/0.075</td>
</tr>
<tr>
<td>SEN Submergence Depth</td>
<td>0.166</td>
</tr>
<tr>
<td>Solidification Constant for Shell Thickness</td>
<td>0.98</td>
</tr>
</tbody>
</table>
Computational Schemes and Boundary Conditions

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<td>2. LES with Wale Model</td>
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</tr>
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<td>Model for Shell Growth</td>
<td>Mass and Momentum Sinks for Liquid Steel</td>
</tr>
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<td>Mass Sink for Argon Phase</td>
</tr>
<tr>
<td>Advection Discretization</td>
<td>1. 1st order upwinding for k-epsilon model</td>
</tr>
<tr>
<td></td>
<td>2. Bounded Central Diff. for LES</td>
</tr>
<tr>
<td>Time Marching Scheme</td>
<td>1. 1st order implicit scheme for k-e model, 0.05 sec time step</td>
</tr>
<tr>
<td></td>
<td>2. 2nd order implicit scheme for LES, 0.002 sec time step</td>
</tr>
<tr>
<td>Pressure Discretization</td>
<td>Body Force Weighted Scheme</td>
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<table>
<thead>
<tr>
<th>Time before collecting statistics</th>
<th>10 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time for the averaging</td>
<td>20 sec</td>
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</tbody>
</table>

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</tr>
</tbody>
</table>

### Argon Gas Injection and Process Parameters

- **Argon Gas Injection at Stopper Rod Tip**
  - 1.73 SLPM

- **Argon Gas Injection at Upper Tundish Nozzle**
  - 4.03 SLPM

- **Plate Argon Injection**
  - 8.02 SLPM

- **SEN Argon Injection**
  - 1.73 SLPM

### Process Parameters

<table>
<thead>
<tr>
<th>Process Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting Speed (m/min)</td>
<td>1.2 m/min</td>
</tr>
<tr>
<td>Argon Injection Method</td>
<td>shown on the left</td>
</tr>
</tbody>
</table>

### Material Properties

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Steel Density (kg/m3)</td>
<td>7520</td>
</tr>
<tr>
<td>Argon Density (kg/m3)</td>
<td>1. At 293 K, 0.55</td>
</tr>
<tr>
<td></td>
<td>2. At 1823 K, 0.291</td>
</tr>
<tr>
<td>Liquid Steel Dynamic Viscosity (Pa·s)</td>
<td>0.006</td>
</tr>
<tr>
<td>Argon Dynamic Viscosity (Pa·s)</td>
<td>1. At 293 K, 2.2816×10⁻⁵</td>
</tr>
<tr>
<td></td>
<td>2. At 1823 K, 8.1825×10⁻⁵</td>
</tr>
<tr>
<td>Argon Mean Bubble Dia (mm)</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Liquid Steel Velocity Distribution at Center Plane between Wide Faces – by k-epsilon Model

- Partial double roll flow pattern is observed (complex flow pattern)
- Jet exiting the port is split into an upward portion heading to meniscus, and a remaining portion impinging the narrow face

Argon Gas Velocity Distribution in the Mold – by k-epsilon with Mixture Model

Gas gathers near the SEN outer surface, with a maximum gas velocity of 1.0~1.2 m/s
Steel/Argon Velocity Distribution at SEN Port Exit – by k-epsilon Model

• Jet swirling at port lower corners
• Part of the jet bends towards meniscus due to the gas drag force
• Maximum jet velocity is found at the port bottom
• Gas gathers both near the top edge of the port and in the lower middle part of port
• Gas “jet” is split into two parts, one moving upward to meniscus and the other part moving with the liquid steel jet

Liquid Steel Velocity Distribution at Center Plane between Wide Faces – by LES with Wale Model

Instantaneous Steel Flow Field at Center Plane

Contour for Instantaneous Liquid Steel Velocity Distribution  Vector Plot for Instantaneous Liquid Steel Velocity
Argon Gas Velocity Distribution in the Mold – by LES with Wale Model

Instantaneous Argon Flow Field at Center Plane

Contour for Instantaneous Argon Gas Velocity Distribution  
Vector Plot for Instantaneous Argon Gas Velocity

- Argon gas is dragged further down the mold by liquid steel, and then floats to the mold top surface

Steel/Argon Velocity Distribution at SEN Port Exit – by LES with Wale Model

Instantaneous Liquid Steel Velocity  
Instantaneous Argon Velocity

- Maximum liquid steel velocity is found at the port corner

- Velocity field is not symmetric for the left and right part of the port, unlike RANS

- Gas gathers both near the top edge of the port and in the lower part of the port
Mean Argon Gas Volume Fraction Distribution
-- RANS VS. LES

- Features in Common for RANS and LES mean:
  1. Gas sheet attaching at SEN inner surface is formed
  2. Higher gas concentration at the upper region of port exit

- Difference:
  1. LES has a gas region spreading to the lower portion of mold, while RANS does not
  2. RANS has higher gas volume fraction at port exit, and the gas sheet in SEN

Time-averaged field over 20 sec

Mean Liquid Steel Velocity Distribution
-- LES VS. RANS

- 20 sec is not long enough for the LES port mean velocities to achieve symmetry

- Major difference observed in gas volume fraction distribution at port exit

-- by LES Wale Model, averaged over 20 sec
-- by k-epsilon Model
Mean Liquid Steel Velocity Distribution  
-- LES VS. RANS

Instantaneous Argon Flow Field at Center Plane between Broad Faces

Conclusions (for part 3)

- By comparing simulation results from LES and URANS, the following features are observed:
  - LES shows less gas gathering at upper SEN port exit, thus less drag force for liquid steel;
  - LES shows a larger gas region, down the liquid pool;
  - Reasonable match between LES mean velocity field (average over 20 sec) and the RANS results is obtained.

- Due to the difference of the two models in predicting argon gas volume fraction distribution, the flow patterns from LES and URANS are slightly different:
  - LES tends to generate double-roll flow patterns, while URANS tends to generate complex flow patterns (especially at high argon injection rate).
Future Work –1

- Use URANS to simulate the transient case proposed in previous slides, to find:
  - meniscus level based on dynamic pressure from the CFD models
  - compare this simulated meniscus level with real measurement to further validate and calibrate the stopper-based model
  - the most accurate curve of SEN flow rate vs. time, via this iterative procedure

- Carry out LES to study the transient flow behavior during the multiple stopper rod movements during this process, to find out:
  - how the flow pattern in the mold is changed by the varying inlet velocity (flow rate)

Future Work –2

- Perform particle transport and entrapment simulations during LES run, to find:
  - how the particles are entrapped due to the flow pattern change
  - preferential locations for the inclusions to get entrapped

- Perform this modeling process for different casting conditions, to find the critical stopper rod moving velocity that can cause sliver defects
Acknowledgment

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