Effect of Nozzle Port Angle on Mold Flow

UIUC: Seong-Mook Cho and Brian G. Thomas
POSTECH: Hyoung-Jun Lee and Seon-Hyo Kim
POSCO: Ji-Joon Kim, Hyun-Jin Cho, Jong-Wan Kim, and Yong-Hwan Kim

Department of Mechanical Science & Engineering
University of Illinois at Urbana-Champaign

Research Scope

- **Objectives:**
  - Optimize nozzle port angle to reduce flow-related surface defects in wide slab
  - Investigate mold flow patterns in wide slab caster with current casting conditions
  - Quantify effect of nozzle port angle on flow pattern and surface velocity, and surface level in a wide slab caster
  - Investigate similarity between water model experiments and plant measurements by comparing surface velocity

- **Methodologies:**
  - 1/3 scale water model experiments to visualize mold flow patterns and quantify surface velocity and surface level fluctuations
  - Plant measurements to measure surface velocity, surface level, slag pool thickness using nail dipping tests and level sensor measurements
  - Computational modeling using Fluent on lab workstation or Blue Waters supercomputer to quantify nozzle flow and mold flow
### Caster Dimensions and Process Conditions

<table>
<thead>
<tr>
<th></th>
<th>Real STS caster (Case R)</th>
<th>Lab (1/3) scale Water model (Case W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting speed</td>
<td>0.8 m/min</td>
<td>0.5 m/min</td>
</tr>
<tr>
<td>Volume Flow rate</td>
<td>256.0 LPM</td>
<td>16.4 LPM</td>
</tr>
<tr>
<td>Mold width</td>
<td>1600 mm</td>
<td>533 mm</td>
</tr>
<tr>
<td>Mold thickness</td>
<td>200 mm</td>
<td>67 mm</td>
</tr>
<tr>
<td>Aspect ratio between mold</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>width and thickness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEN depth</td>
<td>140 mm</td>
<td>46.7 mm</td>
</tr>
<tr>
<td>Nozzle port angle</td>
<td>15° (up) degree</td>
<td>15° (up), 5°(up), -15° (down),</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-30° (down) degree</td>
</tr>
<tr>
<td>Nozzle port size (width x</td>
<td>60 mm x 65 mm</td>
<td>20 mm x 21.7 mm</td>
</tr>
<tr>
<td>height)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nozzle bore (inner / outer)</td>
<td>60 ~ 65 mm (from bottom</td>
<td>20.8 mm (average) / 36.6 mm</td>
</tr>
<tr>
<td></td>
<td>to top) / 110 mm</td>
<td></td>
</tr>
<tr>
<td>Area ratio between two</td>
<td>2.54</td>
<td>2.54</td>
</tr>
<tr>
<td>ports and nozzle bore</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ar gas injection</td>
<td>No gas</td>
<td>10 ml/min (0.06 % volume fraction)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>clear visualization of mold flows</td>
</tr>
</tbody>
</table>

- Flow similarity between 1/3 scale water model (Case W) and real caster (Case R)
- Froude number (ratio of inertia force to gravitational force): $F = \frac{L_W}{L_R}$
- Casting speed $u_c,W$ for 1/3 scale water model: $u_c,W = u_c,R \sqrt{L_W/L_R}$

---

**Physical Water Model Experiments**
Schematic of 1/3 Scale Water Model

- Tundish
- Stopper-rod
- Weir
- SEN
- Flow meter
- Electromagnetic-current sensor
- Ultrasonic displacement sensors
- Mold
- Reservoir
- Pump
- Valve
- 3 Video cameras:
  - V1: NF end view
  - V2: surface bottom-up view
  - V3: WF front view

Electromagnetic Current Sensor (for Surface Velocities) and Ultrasonic Displacement Sensor (for Surface Level Variations) Measurements

Measuring positions of surface flow velocity and surface level
- • Electromagnetic current sensor measurement position
- ▲ Ultrasonic displacement sensor measurement position

- **Measure transient surface velocity** at 10mm below surface on W/4, W/8, 30 mm from NF, using **electromagnetic current sensor** during 1000 sec.
- **Measure transient surface level** on 30mm from SEN, W/4, 30 mm from NF points, using **ultrasonic displacement sensors** during 1000 sec.
Videos to Visualize Mold Flow

- Record 3 videos to show both nozzle and mold flow at same time
- Understand measured surface velocity and surface level with help of recorded videos

* Case W. +5 (up) angle nozzle port

Eddy-current sensor

Modeling and Results Analysis
Quarter Domain and Mesh: Standard $k$-$\varepsilon$ Flow Model with Fluent on Lab Computer (LC)

- Case W-LC. +15° (up) angle nozzle
- Case W-LC. -15° (down) angle nozzle

Full Domain and Mesh: LES with Fluent on Blue Waters (BW)

- Case W-BW. +15° (up) angle nozzle
- Case W-BW. -15° (down) angle nozzle
Governing Equations

- **Case W-LC**: Reynolds Averaged Navier-Stokes (RANS) Model with standard k-ε model
  \[
  \frac{\partial}{\partial x_i} \left( \rho u_i \right) = 0
  \]
  Mass conservation
  \[
  \frac{\partial}{\partial x_j} \left( \rho u_i u_j \right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu + \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right]
  \]
  Momentum conservation

- **Turbulent kinetic energy**
  \[
  \frac{\partial}{\partial x_i} \left( \rho k \right) = \left( \frac{\mu}{\sigma_k} \right) \frac{\partial k}{\partial x_i} + G_k - \rho \varepsilon
  \]

- **Turbulent kinetic energy dissipation rate**
  \[
  \frac{\partial}{\partial x_i} \left( \rho \varepsilon \right) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1t} \frac{\varepsilon}{k} G_k - C_{2t} \rho \frac{\varepsilon^2}{k}
  \]

- **Case W-BW**: Large Eddy Simulation (LES) with Wall-Adapting Local Eddy (WALE) subgrid-scale viscosity model
  \[
  \frac{\partial}{\partial x_i} \left( \rho u_i \right) = 0
  \]
  Mass conservation
  \[
  \frac{\partial}{\partial t} \left( \rho u_i \right) + \frac{\partial}{\partial x_j} \left( \rho u_i u_j \right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu + \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right]
  \]
  Momentum conservation

  \[
  \mu_t = \rho \left( L_s \right)^2 \frac{ \left( S_{ij} S_{ij} \right)^{3/2} }{ \left[ S_{ij} S_{ij} \right]^{3/2} + \left( S_{ij} S_{ij} \right)^{5/4} }\]
  Turbulent viscosity

Boundary Conditions

<table>
<thead>
<tr>
<th><strong>Case W-LC</strong>: Standard k-ε model</th>
<th><strong>Case W-BW</strong>: LES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inlet</strong> (Tundish bottom region)</td>
<td>Constant velocity: 0.00573 m/sec</td>
</tr>
<tr>
<td></td>
<td>Turbulent kinetic energy: 10^{-5} m^2/sec^2</td>
</tr>
<tr>
<td></td>
<td>Turbulent kinetic energy dissipation rate: 10^{-5} m^2/sec^3</td>
</tr>
<tr>
<td><strong>Outlet</strong> (Mold exit)</td>
<td>Constant velocity: 0.0573 m/sec</td>
</tr>
<tr>
<td></td>
<td>Pressure: 0 pascal gauge pressure</td>
</tr>
<tr>
<td></td>
<td>Turbulent kinetic energy for backflow: 10^{-5} m^2/sec^2</td>
</tr>
<tr>
<td></td>
<td>Turbulent kinetic energy dissipation rate for backflow: 10^{-5} m^2/sec^3</td>
</tr>
<tr>
<td><strong>Surface</strong> (interface between water and air)</td>
<td>Stationary wall with 0-shear stress</td>
</tr>
<tr>
<td><strong>Wide face, Narrow face, Stopper-rod, and Nozzle walls (interface between water and )</strong></td>
<td>Stationary wall with no slip</td>
</tr>
</tbody>
</table>
Fluent Performance on BW: Speed-Up Test

- Test problem: Case W-BW
  1/3 water model with 15° (up) nozzle ports
  Mesh of nozzle & mold: ~6.94 million hexahedral cells

\[
\text{Speed-up ratio} = \frac{\text{Computing time per 1 iteration on LC}}{\text{Computing time per 1 iteration on BW}}
\]

- With 96 cores (6 XE nodes), the simulation on Blue Waters runs ~ 41 times faster than on our Lab Computer (LC) (DELL Precision T7600 with Intel Xeon E5-2603 1.80 GHz CPU processor/node with 8 Cores): One iteration on Blue Waters using 96 cores (6 XE nodes) requires ~2.4 seconds of wall clock time. One the other hand, on the lab workstation (using 1 core), the same simulation requires ~ 98.4 seconds of wall-clock time per 1 iteration.

- Fluent computations on Blue Waters show almost linear speed-up with increasing XE nodes.

\[
\begin{array}{c|c}
\text{Total cores used during computation (#)} & \text{Computing time per 1 iteration (sec)} \\
\hline
0 & 5 \\
1 & 5 \\
2 & 5 \\
3 & 5 \\
4 & 5 \\
5 & 5 \\
6 & 5 \\
7 & 5 \\
8 & 5 \\
9 & 5 \\
10 & 5 \\
11 & 5 \\
12 & 5 \\
13 & 5 \\
14 & 5 \\
15 & 5 \\
16 & 5 \\
17 & 5 \\
18 & 5 \\
19 & 5 \\
20 & 5 \\
21 & 5 \\
22 & 5 \\
23 & 5 \\
24 & 5 \\
25 & 5 \\
26 & 5 \\
27 & 5 \\
28 & 5 \\
29 & 5 \\
30 & 5 \\
31 & 5 \\
32 & 5 \\
33 & 5 \\
34 & 5 \\
35 & 5 \\
36 & 5 \\
37 & 5 \\
38 & 5 \\
39 & 5 \\
40 & 5 \\
41 & 5 \\
42 & 5 \\
43 & 5 \\
44 & 5 \\
45 & 5 \\
46 & 5 \\
47 & 5 \\
48 & 5 \\
49 & 5 \\
50 & 5 \\
\end{array}
\]

\[
\begin{array}{c|c}
\text{Speed-up ratio} & \text{Fixed number of total cores: 48 cores} \\
\hline
0 & 5 \\
1 & 5 \\
2 & 5 \\
3 & 5 \\
4 & 5 \\
5 & 5 \\
6 & 5 \\
7 & 5 \\
8 & 5 \\
9 & 5 \\
10 & 5 \\
11 & 5 \\
12 & 5 \\
13 & 5 \\
14 & 5 \\
15 & 5 \\
16 & 5 \\
17 & 5 \\
18 & 5 \\
19 & 5 \\
20 & 5 \\
21 & 5 \\
22 & 5 \\
23 & 5 \\
24 & 5 \\
25 & 5 \\
26 & 5 \\
27 & 5 \\
28 & 5 \\
29 & 5 \\
30 & 5 \\
31 & 5 \\
32 & 5 \\
33 & 5 \\
34 & 5 \\
35 & 5 \\
36 & 5 \\
37 & 5 \\
38 & 5 \\
39 & 5 \\
40 & 5 \\
41 & 5 \\
42 & 5 \\
43 & 5 \\
44 & 5 \\
45 & 5 \\
46 & 5 \\
47 & 5 \\
48 & 5 \\
49 & 5 \\
50 & 5 \\
\end{array}
\]

Fluent Performance on BW: Nodes-Cores Distribution Test

- For using same total cores (#48), speed-up of Fluent computation is more enhanced by increasing compute nodes.

- Applying the distribution of 48 nodes x 1 cores (total 48 cores), shows more speed-up (~43 times vs ~ 41 times) than using total 96 cores (6 nodes x 16 cores): 48 HPC licenses of the Ansys license pool can be saved with more speed-up.
Fluent Performance on BW: BW-Core License Efficiency

Blue Waters (BW)-core license efficiency = Speed-up ratio / total assigned cores = Computing time per 1 iteration on LC / (Computing time per 1 iteration on BW x total assigned cores)

- Use of full 16 cores per 1 node for Fluent calculation on BW, has low efficiency: only 0.4 ~0.5 of lab computer computation using 1 core.
- For using same total cores (#48), BW calculation per 1 core shows much higher efficiency by increasing compute nodes.

Time-averaged Jet Flow Patterns (Case W-LC)

- Back flow from mold to nozzle port, get more with 15 ° (up) nozzle port
- Jet flow in the mold get deeper with -15 ° (down) nozzle port
Transient Swirl from Nozzle Port

- Case W-BW. +15° (up) angle nozzle port
- Case W. +15° (up) angle nozzle port
- Case W-BW. -15° (down) angle nozzle port
- Case W. -15° (down) angle nozzle port

Time-averaged Mold Flow Patterns (Case W-LC)

- With the nozzle port having +15° (up) angle, jet flow goes down deep into wide mold cavity: downward flow is predominant, this is very harmful to produce internal defects.
- Downward -15° degree nozzle port induces a classic double-roll pattern in wide mold.
Vertical Velocity along NF (Case W-LC)

- Jet flow impingement point on narrow face is moved deeper into the mold cavity by decreasing nozzle port angle.
- Upward angle of +15° causes strong downward flow along casting direction.

Turbulent Kinetic Energy in Mold (Case W-LC)

- Jet wobbling is more severe with +15 (up) degree nozzle port, resulting in higher surface flow instability.
Transient Mold Flow Patterns

Predicted: Case W-BW. +15° (up) angle nozzle
Measured: Case W. +15° (up) angle nozzle

Predicted: Case W-BW. -15° (down) angle nozzle
Measured: Case W. -15° (down) angle nozzle

- From both measurements and predictions, the case of 15 (up) angle nozzle shows more variations of jet flow: Jet flow from the nozzle port with 15 (up) angle, induces more severe jet wobbling by producing more swirl flow?

Water Model Measurements: Surface Velocity with +15° (Up) Angle Port

Water Model Measurements: Surface Velocity with +15° (Up) Angle Port

<table>
<thead>
<tr>
<th>Velocity of flow from IR to OR (m/s)</th>
<th>Velocity of flow from NF to SEN (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>30 mm from NF</td>
<td>-0.0175</td>
</tr>
<tr>
<td>W/8</td>
<td>-0.0118</td>
</tr>
<tr>
<td>W/4</td>
<td>0.0218</td>
</tr>
</tbody>
</table>
Water Model Measurements: Surface Velocity with +5° (Up) Angle Port

<table>
<thead>
<tr>
<th>Velocity of flow from IR to OR (m/s)</th>
<th>Velocity of flow from NF to SEN (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>30 mm from NF</td>
<td>-0.0125</td>
</tr>
<tr>
<td>W/8</td>
<td>-0.00473</td>
</tr>
<tr>
<td>W/4</td>
<td>-0.00492</td>
</tr>
</tbody>
</table>

Water Model Measurements: Surface Velocity with -15° (Down) Angle Port

<table>
<thead>
<tr>
<th>Velocity of flow from IR to OR (m/s)</th>
<th>Velocity of flow from NF to SEN (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>30 mm from NF</td>
<td>-0.00381</td>
</tr>
<tr>
<td>W/8</td>
<td>-0.00473</td>
</tr>
<tr>
<td>W/4</td>
<td>-0.00492</td>
</tr>
</tbody>
</table>
Water Model Measurements: Surface Velocity with -30° (Down) Angle Port

Velocity of flow from IR to OR (m/s)
Velocity of flow from NF to SEN (m/s)

Average Standard deviation

<table>
<thead>
<tr>
<th>Distance from NF</th>
<th>Velocity from IR to OR</th>
<th>Standard deviation</th>
<th>Velocity from NF to SEN</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 mm</td>
<td>-0.00158</td>
<td>0.0124</td>
<td>0.0651</td>
<td>0.00762</td>
</tr>
<tr>
<td>&lt;W/8&gt; location</td>
<td>0.0000297</td>
<td>0.0121</td>
<td>0.112</td>
<td>0.0173</td>
</tr>
<tr>
<td>&lt;W/4&gt; location</td>
<td>-0.00305</td>
<td>0.0155</td>
<td>0.105</td>
<td>0.0172</td>
</tr>
</tbody>
</table>

Model Validation (Results of Case W and Case W-LC) : Horizontal Surface Velocity

RANS model using standard k-ε model agrees with water model measurements of surface velocity and its fluctuation.

*Error bars: expected velocity fluctuations = $\sqrt{\frac{1}{3}u'^2} = \sqrt{\frac{2}{3}k}$
Model Validation (Results of Case W and Case W-LC) : Surface Level

Average surface level profile ($h_i$):

$$h_i = \frac{P_i - P_{AVG}}{\rho_w g}$$

Surface level fluctuation ($\Delta h_i$):

$$\Delta h_i = \frac{k}{g}$$

- RANS model using standard k-ε model agrees with water model measurements of average surface level profile
- Discrepancy of level fluctuation: Low resolution (0.5 mm) of level sensor is not sufficient to capture level fluctuations in water model mold.

Effect of Port Angle on Average of Velocity Components

- The cases of downward port angle show higher surface velocity towards SEN, than upward angle cases
- -15° (down) angle port causes the highest surface velocity component towards SEN.
- Upward angle port produces more asymmetric flow between IR and OR than downward angle port.
Effect of Port Angle on Fluctuations of Velocity Components

- Velocity fluctuations towards both SEN and OR, increase with increasing nozzle port angle.

### Power Spectrum Analysis of Transient Surface Velocity towards SEN of Water Model measurements

- Upward port angle induces stronger surface velocity variations.
- For the nozzle port with +15° (up) degree angle, the frequency of ~0.11 Hz, for asymmetric flow past the SEN predicted using Honeyands and Herbertson’s relation, is found in the power spectrum.

Nail Dipping Tests

Dipping test details

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total tests (for each IR and OR region)</td>
<td>5</td>
</tr>
<tr>
<td>interval of each test</td>
<td>1 min</td>
</tr>
<tr>
<td>Dipping time</td>
<td>3 sec</td>
</tr>
</tbody>
</table>

Empirical equation for surface velocity magnitude\(^1\):

Surface velocity magnitude: 
\[ u_s (\text{m/s}) = 0.624 \cdot (\varphi_{\text{lump}} (\text{mm}))^{-0.696} \cdot (h_{\text{lump}} (\text{mm}))^{0.567} \]

\(^1\) Liu et al., Proc. of TMS 2011, TMS, Warrendale, PA, USA

Comparison of Plant Measurements (Case R), 1/3 Scale Water Model Measurements (Case W), Computational Model (Case W-LC): All Scaled-Up of Surface Velocity for Real Caster

• Limitation to understand surface flow in real wide-mold caster from water model measurement and computational modeling of water model: Computational modeling for real caster case including steel shell and liquid mold flux layer is needed

Scale up method:

\[ u_{s,R} = u_{s,W} \times \left( \frac{u_{\text{in},R}}{u_{\text{in},W}} \right)^{1.73} \]

\[ u_{s,R} = \frac{u_{c,R} \times w_R \times t_R}{\pi (r_R)^2} \]

\[ = \frac{u_{c,W} \times w_W \times t_W}{\pi (r_W)^2} \]

\[ = \frac{L_R}{L_W} \]

\[ u_{s,R} = 1.73 \times u_{s,W} \]

\( s \): surface, \( i\): nozzle inlet, \( r \): nozzle inner radius, \( w \): mold width, \( t \): mold thickness, \( L \): process length scale

\(^*\) Sigh et al., MMTB, Vol. 44B, 2013, p.1201-1221
Summary:
Modeling and Measurements

- 1/3 scale water model experiments, plant measurements, and computational modeling using both lab computer and Blue Waters supercomputer, were performed to investigate effect of nozzle port angle on nozzle and mold flow, for reducing surface defects in wide slab.
- Reynolds-Averaged Navier-Stokes (RANS) model using standard k-ε model on lab computer and Large Eddy Simulation (LES) on Blue Waters supercomputer, were used to quantify time-averaged and dependent flow in 1/3 scale water model.
- RANS model shows a very good quantitative match with average surface velocity profile across 1/3 scale water model.
- LES model can capture transient nozzle swirl and jet wobbling, which is important transient flow phenomena to cause surface instability, related to surface defect formation with nozzle port angle effect.
- Water model surface velocities near narrow face exceed those in real wide-mold caster.
- Transient flow modeling including steel shell and liquid mold flux layer, is likely needed to understand surface flow variations (especially, near NF) in wide mold of real caster.

Summary:
Effect of Nozzle Port Angle & Suggestion

- Jet flow from +15° (up) nozzle port shows more severe wobbling than +5°(up), -15° (down), -30°(down) ports; this jet impinges first on top surface causing surface instability (the highest surface velocity variations even though it has the lowest surface velocity).
- Higher surface velocity fluctuations not always caused by faster surface flow: surface instability depends on casting conditions.
- Maximum average surface velocity is produced by port angle of -15° (down).
  - Deeper port angle (-30° (down)) has slower surface velocity.
  - Shallowest port angle (+5° (up) and +15° (up) degree) has slower surface velocity.
- Maximum surface velocity when jet impinges on NF at upward angle: Surface velocity slower if jet first impinges on NF at downward angle or near top surface or corner.
- Up-angled nozzle with non-optimized SEN depth could be detrimental in causing both severe surface instability (surface defects) and abnormal downward flow (internal defects) deep into mold cavity.
- Worst flow pattern (from +15° in this work) is unstable between single and double-roll: pressure sucks jet up to impinge top surface; or down to impinge on NF; wobbling between causes instability and defects.
- Deeper submergence is suggested for up-angled nozzle in this caster system to enable jet flow-hit to impinge first on NF.
- High-frequency low-amplitude turbulence is optimal to get mixing, heat transfer to meniscus without surface instability; Avoid High-power lower-frequency oscillations with large spatial variations.
Acknowledgments

• Continuous Casting Consortium Members (ABB, AK Steel, ArcelorMittal, Baosteel, JFE Steel Corp., Magnesita Refractories, Nippon Steel and Sumitomo Metal Corp., Nucor Steel, Postech/Posco, SSAB, ANSYS/Fluent)

• Blue Waters / National Center for Supercomputing Applications (NCSA) at UIUC

• POSCO (Grant No. 4.0011721.01)

• Dr. Ahmed Taha, NCSA for help with the Fluent Module Implementation into Blue Waters

• Hyun-Na Bae, Dae-Woo Yoon, and Seung-Ho Shin POSTECH for help with the 1/3 scale water model experiments