Hook formation near slab corners and prediction of argon gas bubble size in the slab casting mold

Go-Gi Lee
(Visiting Scholar from POSTECH, South Korea)

Brian G. Thomas

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

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- Korea Research Foundation
- Professor Brian G. Thomas
- Professor Seon-Hyo Kim
- Dr. Ho-Jung Shin, POSTECH
1. Investigation of 3-D Frozen Meniscus Shape

3-D Frozen Meniscus Region - corners of slab

- Micrographs of the hook come from 2-D vertical section view of certain location
- Near the corners of the slab: deepest hook depth at corners; complex 3-D hook shape
  → 3-D shape of frozen meniscus at corners is not clear
Metallurgical Method

Sample size: 20mm(width) * 13mm(depth) * 30mm(height)

< Location of sample >

< Definition of axes >

- Ten micrographs (2-D vertical section view) were obtained from YZ plane according to X distance (~6mm) from corners

Casting Conditions

- Slab thickness: 230 mm; Slab width: 1300 mm; Casting speed: 1.45 m/min; Pour temperature: 1571°C

Mold oscillation conditions

<table>
<thead>
<tr>
<th>Stroke (mm)</th>
<th>Frequency (cpm)</th>
<th>Modification ratio for non-sinusoidal mode (%)</th>
<th>Negative strip time (sec)</th>
<th>Positive strip time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>174</td>
<td>12</td>
<td>0.100</td>
<td>0.241</td>
</tr>
</tbody>
</table>

Steel composition of ultra-low carbon steel (wt. %)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 0.005</td>
<td>0.08</td>
<td>≤ 0.005</td>
<td>~ 0.015</td>
<td>~ 0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01 ~ 0.02</td>
<td>0.05</td>
<td>~ 0.04</td>
</tr>
</tbody>
</table>

Mold powder composition and properties

<table>
<thead>
<tr>
<th>Chemical composition (wt. %)</th>
<th>Basicity</th>
<th>SiO₂</th>
<th>CaO</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>TiO₂</th>
<th>Fe₂O₃</th>
<th>MnO₂</th>
<th>P₂O₅</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>F</th>
<th>B₂O₃</th>
<th>Li₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.10</td>
<td>36.3</td>
<td>39.8</td>
<td>0.84</td>
<td>5.97</td>
<td>0.18</td>
<td>0.34</td>
<td>0.03</td>
<td>0.03</td>
<td>3.43</td>
<td>0.11</td>
<td>6.72</td>
<td>0</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Properties</th>
<th>Solidif. Temperature (°C)</th>
<th>Softening Temperature (°C)</th>
<th>Melting Temperature (°C)</th>
<th>Viscosity at 1300 °C (Poise)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1149</td>
<td>1170</td>
<td>1180</td>
<td>3.21</td>
</tr>
</tbody>
</table>
Actual Measurement of Micrograph

Micrograph of YZ plane at X = 1.7mm

- Blue color: Upper line of frozen meniscus
- Red color: Lower line of frozen meniscus
- Gray color: Profile of oscillation mark
- Green color: Tip of frozen meniscus

Analysis of Micrographs

- Blue color: Upper line of frozen meniscus
- Red color: Lower line of frozen meniscus
- Gray color: Profile of oscillation mark
- Green color: Tip of frozen meniscus

< Micrographs according to the X direction >
Investigate of Frozen Meniscus Shape

Hook characteristics:
Continuous defect along the OM; 3-D structure

Conclusions

- Frozen meniscus shape near the corner of slabs is investigated with metallurgical analysis:
  - Micrographs show the 3-D frozen meniscus shape
  - Hook is continuous defect at the oscillation mark running completely around the strand perimeter
  - Deepest hook depth appears near corners
2. Investigation of Argon Bubble Size in Water Model using Porous Nozzle Refractory

Water Model Apparatus (1/3 scale)

Size of MgO refractory brick: 14mm(W)*44mm(L)*17mm(D)
Schematic of Upper Tundish Nozzle in Water Model

**Conditions of the Experiment**

- **Fixed test conditions**
  - Submergence depth: 60mm
  - SEN outlet port angle: 35° downward
  - Height of tundish bath: 330mm

- **Factors**
  - Total gas flow rate: 0.1, 0.2, 0.3 l/min
  - Mean water velocity: 0.96, 1.10, 1.25 m/s

<table>
<thead>
<tr>
<th>Test conditions in water model</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Brick 1</th>
<th>Brick 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fired B.D. (g/cc)</td>
<td>2.9</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>16.2</td>
</tr>
<tr>
<td><strong>Permeability (nPm)</strong></td>
<td><strong>7.52</strong></td>
</tr>
<tr>
<td>Modulus of rupture (psi)</td>
<td>1085</td>
</tr>
</tbody>
</table>

*< Properties of MgO refractory bricks >*

Note: MgO uses to simulate the dolomite refractories
Similarity Analysis between Steel Caster & Water Model

Dimensionless groups

\[
Fr_{liq} = \frac{\text{Inertial force due to liquid momentum}}{\text{Buoyancy force}} = \frac{\rho_l U_{liq}^2}{(\rho_l - \rho_g) D g}
\]

\[
Fr_{gas} = \frac{\text{Inertial force due to gas momentum}}{\text{Buoyancy force}} = \frac{\rho_g D v_{gas}^2}{(\rho_l - \rho_g) D g}
\]

\[
Re_{liq} = \frac{\text{Inertial force due to liquid momentum}}{\text{Viscous force of liquid}} = \frac{\rho_l D U_{liq}}{\mu_l}
\]

\[
Re_{gas} = \frac{\text{Inertial force due to gas momentum}}{\text{Viscous force of gas}} = \frac{\rho_g D v_{gas}}{\mu_g}
\]

\[
We_{liq} = \frac{\text{Inertial force due to liquid momentum}}{\text{Surface tension force}} = \frac{\rho_l D U_{liq}^2}{\gamma D}
\]

\[
We_{gas} = \frac{\text{Inertial force due to gas momentum}}{\text{Surface tension force}} = \frac{\rho_g D v_{gas}^2}{\gamma D}
\]

where,

\(D\) : average bubble diameter at a pore,
\(d\) : gas injection pore diameter,
\(\rho_l\) : liquid density,
\(\rho_g\) : gas density,
\(\mu_l\) : liquid viscosity,
\(\mu_g\) : gas viscosity,
\(U_{liq}\) : liquid velocity,
\(v_{gas}\) : gas velocity,
\(\gamma\) : liquid/gas surface tension coefficient,
\(g\) : gravitational acceleration.

Physical properties used in calculation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Water-air system</th>
<th>Steel-hot Ar system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid density ((\rho_l, \text{kg/m}^3))</td>
<td>1000</td>
<td>7020</td>
</tr>
<tr>
<td>Gas density ((\rho_g, \text{kg/m}^3))</td>
<td>1.331(^{\circ})</td>
<td>0.446(^{\circ})</td>
</tr>
<tr>
<td>Liquid viscosity ((\mu_l, \text{kg/m}\cdot\text{s}))</td>
<td>0.001</td>
<td>0.0056</td>
</tr>
<tr>
<td>Gas viscosity ((\mu_g, \text{kg/m}\cdot\text{s}))</td>
<td>1.70E-05</td>
<td>7.42E-05</td>
</tr>
<tr>
<td>Surface tension coefficient ((\gamma, \text{N/m}))</td>
<td>0.073</td>
<td>1.192</td>
</tr>
</tbody>
</table>

\(^{\circ}\) Note: Gas density was calculated for the temperature in liquid and the pressure due to the height of liquid in tundish (see appendix 2)

Ref.) H. Bai: Ph. D. Thesis. UIUC, Urbana, IL, 2000

Liquid Flow Rate between Two Systems

From mass balance

\[
Q_w = U_{W,\text{nozzle}} \cdot A_{W,\text{nozzle}} \quad \therefore \quad U_{W,\text{nozzle}} = \frac{Q_w}{A_{W,\text{nozzle}}}
\]

We choose the same liquid velocity between two systems, because the refractory geometry scale is 1:1

\[
U_{W,\text{nozzle}} = U_{S,\text{nozzle}} \quad \therefore \quad Q_s = U_{S,\text{nozzle}} \cdot A_{S,\text{nozzle}}
\]

\[
V_c = \left(\frac{Q_s}{\text{Cross - sectional area of the strand}}\right)
\]

Table. Relationship between the liquid flow rate and casting speed

<table>
<thead>
<tr>
<th>Water flow rate (l/min)</th>
<th>Q_w</th>
<th>28.2</th>
<th>32.5</th>
<th>36.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid velocity in nozzle (m/sec)</td>
<td>U_{W,\text{nozzle}}=U_{S,\text{nozzle}}</td>
<td>0.96</td>
<td>1.10</td>
<td>1.25</td>
</tr>
<tr>
<td>Steel throughput (m³/min)</td>
<td>Q_s</td>
<td>0.25</td>
<td>0.29</td>
<td>0.33</td>
</tr>
<tr>
<td>Casting speed (m/min, 230mm*1500mm slab)</td>
<td>V_c</td>
<td>0.74</td>
<td>0.85</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Note) Bore diameter of SEN is 25mm in water model and 75mm in steel caster, respectively.
Gas Flow Rate Ratio caused Surface Area of Refractory

\[ Q_{\text{air-out}} = \frac{Q_{\text{air-in}}}{N_{T,W}} = \frac{Q_{\text{air-in}}}{N_{U,W} \cdot A_W} \]

\[ Q_{\text{Ar-hot}} = \beta \cdot \frac{Q_{\text{Ar-cold}}}{N_{T,S}} = \beta \cdot \frac{Q_{\text{Ar-cold}}}{N_{U,S} \cdot A_S} \]

\(< \text{Schematic of water model experiment} >\)

\(< \text{Schematic of steel caster} >\)

\[ Q_{\text{Ar-hot}} = \beta \cdot \frac{Q_{\text{Ar-cold}}}{A_W} \cdot \frac{A_S}{A_{\text{gas}}} \cdot \frac{Q_{\text{air-in}}}{Q_{\text{Ar-in}}} \]

\(N_f:\text{Total active sites on inner wall surface of refractory}\)

\(N_c:\text{Active sites per unit area of refractory}\)

\(A:\text{Inner wall area of refractory}\)

Summary of Dimensionless Number Analysis

<table>
<thead>
<tr>
<th>Dimensionless number</th>
<th>(Q_{\text{air-in}}) (Q_{\text{Ar-cold}})</th>
<th>(Q_{\text{air-in}}) (Q_{\text{Ar-cold}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F_{\text{liq}})</td>
<td>0.07</td>
<td>0.285</td>
</tr>
<tr>
<td>(R_{\text{liq}})</td>
<td>0.087</td>
<td>0.356</td>
</tr>
<tr>
<td>(W_{\text{liq}})</td>
<td>0.03</td>
<td>0.123</td>
</tr>
<tr>
<td>(F_{\text{gas}})</td>
<td>0.0152</td>
<td>0.067</td>
</tr>
<tr>
<td>(R_{\text{gas}})</td>
<td>0.005</td>
<td>0.026</td>
</tr>
<tr>
<td>(W_{\text{gas}})</td>
<td>0.01</td>
<td>0.044</td>
</tr>
</tbody>
</table>

High liquid velocity (\(U>1.4\text{m/s}\)):

\(F_{\text{liq}}\) \(R_{\text{liq}}\) \(W_{\text{liq}}\)

\(F_{\text{gas}}\) \(R_{\text{gas}}\) \(W_{\text{gas}}\)

At high liquid velocity (\(U>1.4\text{m/sec}\)):

\(D_{\text{air}} \approx D_{\text{Ar}}\) at the same gas flow rate

Matching all of the dimensionless groups at the same time is impossible
Active Sites in Stagnant Flow

- Number of active site and bubble size through the porous refractory in stagnant flow are mainly dependent on the texture of porous refractory.
- Generally speaking, active site increases as gas flow rate increases.

Comparison of Mean Active Sites between Flowing and Stagnant Flow

- Test conditions:
  - Low permeability (7.52nPm)
  - Mean liquid velocity: 1.25 m/s
  - Total gas flow rate = 0.1 l/min
  - Camera speed: 4000 frames/s

- Active sites in downward flow are about 2 times those in stagnant flow.
- Gas flow rate per site of high permeability is slightly higher than that of low permeability in downward-flowing flow at the same total gas flow rate.
Calculation of Total Active Sites in the Steel Caster Nozzle Wall

\[ N_U = 2.3154 \ln(Q_T) + 9.2263 \]

\( Q_T = (\text{Total gas flow rate - cold, l/min}) \)

\( A (\text{Inner wall area of refractory*, cm}^2) = 6.2 \text{ cm}^2 \)

\( N_T (\text{Total active sites, #}) = 34 \text{ #} \)

\( \beta (\text{Gas volume expansion coefficient**}) = 0.18 \)

\( \beta \times Q_T \times \frac{A_s (\text{cm}^2) \times N_U (\text{#/cm}^2)}{} \)

\( A_s = 353.4 \text{ cm}^2 \)

\[ \frac{0.069}{0.098} = 0.125 \quad 0.151 \]

\[ \frac{0.073}{0.096} = 0.119 \quad 0.140 \]

• Low permeability is much more active sites

Comparison of Estimated Mean Gas Flow Rate per Site between Two Systems

\[ \beta \times Q_T \times \frac{A_s (\text{cm}^2) \times N_U (\text{#/cm}^2)}{} \]

\( \beta = 0.18 \)

\( Q_T = (\text{Total gas flow rate - cold, l/min}) \)

\( A_s (\text{cm}^2) \)

\( N_U (\text{Mean active sites per unit area on inner wall of refractory}) \)

\( N_T (\text{Total active sites on inner wall area, #}) \)

\( Q_T (\text{Total gas flow rate - cold, l/min}) \)

\( \beta (\text{Gas volume expansion coefficient**}) \)

\( A_s (\text{cm}^2) \)

\( N_T (\text{Total active sites on inner wall area, #}) \)

\( \beta \times Q_T \times \frac{A_s (\text{cm}^2) \times N_U (\text{#/cm}^2)}{} \)

Similarity of mean gas flow rate per site between two systems

\( \Rightarrow \) It makes the result of water model is meaningful
Bubble Size Distributions: measured in water model nozzle

- Bubble size variations increase with increasing gas flow rate and increasing bubble diameter

Effect of Liquid Velocity and Gas Flow Rate on Bubble Diameter (water model)

- The mean bubble size increases with increasing gas flow rate and decreasing liquid velocity
Comparison of Measured and Predicted Gas Bubble Size

**Comparison of Estimated Ar Bubble Size between Steel Caster and Water Model using the Bai’s Prediction**

Ref.) Bai & Thomas, Met. Trans., 2001
Conclusions

- Investigation of Ar bubble size in water model nozzle using porous refractory
  - Micro texture of the porous refractory greatly affects injected gas behavior in stagnant flow
  - Active sites in downward-flowing flow are about two times compare with stagnant measurement
  - Although matching different dimensionless groups at the same time is impossible, the similarity of mean gas flow rate per site between water model and steel caster is good
  - Bubble size variations increase with increasing gas flow rate and increasing bubble diameter
  - Mean bubble size increases with increasing gas flow rate and decreasing liquid velocity
  - The match of mean bubble size between the previous model prediction by Bai and the experimental data is reasonably good

Appendix 1. Surface Area Ratio

Effective length of UTN considered distribution of Ar gas velocity

Distribution of Ar gas velocity

B. G. Thomas & Z. Hashisho, CCC Annual Report, 2005

Cylinder-like refractory in actual plant
Surface area ($A_S$) = 353.4cm$^2$

Rectangular refractory fixed in water model
Surface area ($A_W$) = 6.2cm$^2$
Appendix 2. Calculation of Gas Density

\[ \rho_g \text{ is density of gas} \]
\[ \rho_g = \frac{\text{weight (m)}}{\text{volume (V)}} \quad (1)' \]

Ideal gas equation is \( PV = nRT \) \quad (2)'

Combining Eqs. (1)' & (2)' gives
\[ \rho_g = \frac{mP}{nRT} \]

1) Steel-Ar system
\[ \rho_{g, \text{Ar}} = \left( \frac{P}{P_{\text{std}}} \right) \left( \frac{T_{\text{std}}}{T_{\text{Ar}}} \right) = \left( \frac{P_{\text{std}} + \rho_{g} \cdot g \cdot H_s}{P_{\text{std}}} \right) \left( \frac{273}{1833} \right) \]
\[ = 1.679 \times \left( \frac{1}{6.714} \right) = \frac{1}{4} \times 0.25 \]
\[ \therefore \rho_{g, \text{Ar}} = 0.25 \times \rho_{g, \text{std}} = 0.446 \text{kg/m}^3 \]

\[ \therefore \text{Ar volume expansion coefficient relative to STP} = 4 \]

2) Water-air system
\[ \rho_{\text{w, std}} = \left( \frac{P}{P_{\text{std}}} \right) \left( \frac{T_{\text{std}}}{T_{\text{w}}} \right) = \left( \frac{P_{\text{std}} + \rho_{\text{w}} \cdot g \cdot H_w}{P_{\text{std}}} \right) \left( \frac{273}{273} \right) \]
\[ = 1.032 \]
\[ \therefore \rho_{\text{w, std}} = 1.032 \times \rho_{\text{w, std}} = 1.331 \text{kg/m}^3 \]

\[ \therefore \rho_{\text{Ar-out}} = 0.446 \text{kg/m}^3 \]
\[ \therefore \rho_{\text{air-out}} = 1.331 \text{kg/m}^3 \]

Table. Properties used in calculation

<table>
<thead>
<tr>
<th>Standard pressure</th>
<th>( P_{\text{std}} )</th>
<th>101325 Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Density of the liquid (kg/m(^3))</td>
<td>( \rho_{\text{w}} )</td>
<td>1000 kg/m(^3)</td>
</tr>
<tr>
<td>Density of steel</td>
<td>( \rho_{\text{s}} )</td>
<td>7020 kg/m(^3)</td>
</tr>
<tr>
<td>The Density of the gas (kg/m(^3) , STP)</td>
<td>( \rho_{\text{Ar}} )</td>
<td>1.783 kg/m(^3)</td>
</tr>
<tr>
<td>Density of air gas</td>
<td>( \rho_{\text{Air}} )</td>
<td>1.29 kg/m(^3)</td>
</tr>
<tr>
<td>The height of steel in tundish</td>
<td>( H_s )</td>
<td>1.0 m</td>
</tr>
<tr>
<td>The height of water in tundish</td>
<td>( H_w )</td>
<td>0.33 m</td>
</tr>
</tbody>
</table>