Investigation of Flow Pattern, Surface Behavior, and Mold Slag Entrainment using an Oil-Water Model and CFD Model

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Research Background:
Slag Entrainment Mechanisms

1. Surface level fluctuation[2-4]
2. Meniscus freezing, hook formation
3. Vortex Formation[5,6]
4. Shear layer instability[7-9]
5. Upward flow[10]
6. Argon bubble interactions/slag foaming
8. Surface wave instability
9. Surface balding

- Primary mechanism of slag entrainment depends on casting conditions, but likely involve mechanisms 1,8 (mainly surface) and 3, 4, 5, 7, 9 (mainly interior) which all have both quasi-steady and transient aspects.
- Investigate surface flow and entrainment phenomena using water model experiments, plant measurements and advanced computational models to quantify slag entrainment in a continuous slab casting
- Computational model is available to evaluate slag entrainment criteria
Research Scope

- **Objectives:**
  - Understand flow patterns, surface behavior, related to slag entrainment in mold of continuous slab caster.
  - Develop computational models of “liquid slag/molten steel interface motion and slag entrainment at mold surface”.
  - Apply the validated computational model with water model experiments, to get insight into slag entrainment mechanism in mold of continuous slab casting.

- **Methodologies:**
  - **1/3 scale water model experiments** to understand mold flow pattern and evaluate slag entrainment mechanisms.
  - Computational modeling to evaluate 3D-Volume Of Fluid (VOF) model to predict mold flow pattern for 1/3 scale water model of conventional slab caster with clog nozzle and validate the model prediction with water model experiments.

Review of 1/3 Scale Water Model Measurements
### 1/3 Scale Water Model

![Diagram of 1/3 Scale Water Model](image)

### Caster Dimensions and Process Conditions

<table>
<thead>
<tr>
<th>Caster dimensions</th>
<th>1/3 scale water model</th>
<th>Real caster (normal case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle bore diameter (inner/outer)</td>
<td>25 mm/46 mm</td>
<td>75 mm/138 mm</td>
</tr>
<tr>
<td>Nozzle bottom well depth</td>
<td>6.3 mm</td>
<td>19 mm</td>
</tr>
</tbody>
</table>
| Nozzle port area | non-clogged port: 23.3 mm x 26.7 mm  
clogged port: 13.5 mm x 15.4 mm | 69.9 mm x 80.1 mm |
| Nozzle port angle | 35 down degree at both top and bottom | 35 down degree at both top and bottom |
| Mold thickness | 77 mm | 231 mm |
| Mold width | 500 mm | 1500 mm |

<table>
<thead>
<tr>
<th>Process conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume flow rate (Water or Steel)</td>
<td>34.4 LPM</td>
</tr>
<tr>
<td>Casting speed</td>
<td>( U_{c,W} = 0.89 \text{ m/min} )</td>
</tr>
<tr>
<td>Submerged depth of nozzle</td>
<td>60 mm</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): 
  \[ \left( \frac{u \sqrt{gL}}{R} \right)_W = \left( \frac{u \sqrt{gL}}{R} \right)_R \]
- Casting speed \( u_{c,W} \) for 1/3 scale water model: 
  \[ u_{c,W} = u_{c,R} \frac{L_W}{L_R} \]
Details of Nozzle Dimensions

To investigate effect of asymmetric mold flow on surface behavior and mold slag entrainment, two cases (No-clog nozzle and Clog nozzle) are compared.

Clog nozzle has 67%-clog part in upper region of left port.

Comparison of Properties between Oil/Water and Mold Flux/Steel System

Higher density ratio, lower dynamic viscosity of upper layer, and lower interfacial tension produce more slag entrainments in silicon oil/water system than slag/steel system.

It is needed to understand entrainment phenomena in oil/water system and develop computational model for slag/steel system of real caster.
Mold Surface Behaviors in Oil/Water System

- **No-clog case** shows surface level fluctuations, max ~ 20mm (~ 200 % of oil thickness average (10mm)). On the other hand, clog case produces much more severe surface instability over ~ 60 mm (~ 600 % of oil thickness average), which makes oil reach jet flow from nozzle port.

- **With clog nozzle**, surface instability is high enough to *drag oil* finger deep into nozzle port flow, resulting in oil **entainment**.

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Slag Entrainment Phenomena

- Abnormally fast surface flow induces interface instability between oil and water phase, dragging oil finger into water pool.

- Entrained oil reaches nozzle port.

- Entrained oil is “broken-up” into small sizes.

- Jet flow takes oil bubbles deep into the mold.
Critical Surface Velocity for Entrainment:
Shear Layer Instability

- Shear layer instability mechanism is most likely to occur in the surface region where surface velocity shows a maximum
- Kelvin-Helmholtz (K-H) instability\(^7,8\):
  \[ \Delta V_{\text{crit}} = \sqrt{\frac{4g(\rho_l - \rho_u)\Gamma_{ul}}{\rho_u}} \left( \frac{1}{\rho_u} + \frac{1}{\rho_l} \right)^2 \]
- Funada-Joseph (F-J) instability\(^9\):
  \[ \Delta V_{\text{crit}} = \sqrt{\frac{4g(\rho_l - \rho_u)\Gamma_{ul}}{\rho_u}} \left( \frac{\mu_l + \mu_u}{\rho_l\mu_l^2 + \rho_u\mu_u^2} \right)^2 \]

<Entrainment by shear layer instability\(^1\>:

- With employing slag viscosity, F-J predicts smaller critical surface velocity

<table>
<thead>
<tr>
<th>( \Delta V_{\text{crit}} )</th>
<th>K-H</th>
<th>F-J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil/water</td>
<td>0.102 m/sec</td>
<td>0.072 m/sec</td>
</tr>
<tr>
<td>Slag/steel</td>
<td>0.30 m/sec</td>
<td>0.27 m/sec</td>
</tr>
</tbody>
</table>

Critical Surface Velocity for Entrainment:
Upward Flow

Harman and Cramb\(^10\):
\[ V_{\text{critical}} = 3.065 \Gamma_{ul}^{0.232} g^{0.115} \delta^{0.365} \psi \frac{(\rho_l - \rho_u)^{0.215}}{\rho_u^{0.694}} \mu_u^{0.231} \mu_l^{0.043} \]

<table>
<thead>
<tr>
<th>( V_{\text{critical}} )</th>
<th>Critical surface velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>Density (kg/m(^3))</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Dynamic viscosity (kg/m·sec)</td>
</tr>
<tr>
<td>( \Gamma )</td>
<td>Interfacial tension between upper and lower layer (N/m)</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Upper layer thickness (m)</td>
</tr>
<tr>
<td>( g )</td>
<td>Gravity acceleration (m/sec(^2))</td>
</tr>
</tbody>
</table>

<Entrainment by upward flow with (a) dragging mode, (b) cutting mode\(^1\)>

<table>
<thead>
<tr>
<th>( V_{\text{critical}} )</th>
<th>Critical:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil/water (m/sec)</td>
<td>0.10 m/sec</td>
</tr>
<tr>
<td>Slag/steel (m/sec)</td>
<td>0.44 m/sec</td>
</tr>
</tbody>
</table>
Comparison of Critical Velocity for Entrainment between Predictions and Measurement (1/3 Scale Water Model)

- Predicted critical surface velocity. Measured critical velocity for entrainment is higher than predicted ones by the reported eqns for shear instability (K-H, F-J) and upward flow (Harman and Cramb).
- Cho’s and Hibbeler’s simulation results well-match with the measured one, indicating excellent potential computational modeling for future work.
- Computational modeling work is needed to understand slag entrainment mechanism in

3D-VOF Model Test: LES coupled VOF Modeling of Surface Motion and Entrainment Phenomena (Modeling of Oil/Water System in 1/3 scale water model)
Governing Equations

Large Eddy Simulation (LES) coupled with Volume Of Fluid (VOF) for three-phase (air/oil/water) flows

- **VOF** (Volume fraction of each phase):
  \[
  \frac{\partial \alpha_{\text{air}}}{\partial t} + \nabla \cdot \left( \alpha_{\text{air}} \cdot \vec{u}_{\text{air}} \right) = 0 \quad \frac{\partial \alpha_{\text{oil}}}{\partial t} + \nabla \cdot \left( \alpha_{\text{oil}} \cdot \vec{u}_{\text{oil}} \right) = 0 \quad \alpha_{\text{water}} = 1 - \alpha_{\text{oil}} - \alpha_{\text{air}}
  \]
  
  - **Continuity**:
    \[
    \frac{\partial \rho_{\text{mix}}}{\partial t} + \nabla \cdot \left( \rho_{\text{mix}} \vec{u} \right) = 0 \quad \rho_{\text{mix}} = \alpha_{\text{water}} \rho_{\text{water}} + \alpha_{\text{oil}} \rho_{\text{oil}} + \alpha_{\text{air}} \rho_{\text{air}}
    \]
  
  - **Momentum conservation**:
    \[
    \rho_{\text{mix}} \frac{\partial \vec{u}}{\partial t} + \rho_{\text{mix}} \vec{u} \cdot \nabla \vec{u} = -\nabla p + \nabla \cdot \left[ \mu_{\text{mix}} \left( \nabla \vec{u} + \nabla^T \vec{u} \right) \right] + \rho_{\text{mix}} g + \mathbf{F}_{\text{interface}}
    \]

Domain and Mesh

Hexahedral cells: ~2.8 million

77%-clogged port
Boundary Conditions and Computation Details

- **Boundary conditions:**
  
  - Inlet (tundish) 0.00149 m/s
  - Air/Oil interface and Oil/Water interface interior
  - Top surface of air layer 0 shear stress
  - Stopper-rod walls, Nozzle walls, wide faces, and narrow faces No slip

- **Initial input values:**
  - Velocity field of steady-state single-phase (water) flow using standard k-ε CFD model
  - 100% air fraction in initial air layer, 100% oil fraction in initial oil layer,
  - 100% water fraction in initial water pool

- **Time step:** 0.001 sec

- **Contact angle[^12-14]:**
  - air/water/acrylic: 69.1°
  - Air/oil/acrylic: 26.6°
  - Oil/water/acrylic: 76.1°

- **Interfacial tension:**
  - Oil / water interfacial tension: 0.247 N/m
  - Air / oil interfacial tension: 0.209 N/m

- **Initial input values:**
  - Velocity field of steady-state single-phase (water) flow using standard k-ε CFD model
  - 100% air fraction in initial air layer, 100% oil fraction in initial oil layer,
  - 100% water fraction in initial water pool

- **Time step:** 0.001 sec
Planes and Points in the Domain

1: center-middle plane between IR and OR
2,3 : 15mm from plane 1
4,5 : 32mm from plane 1
6: center-middle plane between right and left NF
7: 42mm from plane 6
8: 65mm from plane 6
9: 125mm from plane 6
10: AVG oil/water interface
11: 5mm below plane 10
12: 10mm below plane 10

<Points>
P1 (512, -23, 0)
P2 (512, 23, 0)
P3 (600, -125, 0)
P4 (600, 125, 0)
P5 (433.8, -125, 0)
P6 (433.8, 125, 0)

<Planes in the mold domain>
<Points in the mold domain>

Plane data: collected at 0.05 s interval
Point data: collected at 0.001s interval

77 mm (mold thickness) X 500 mm (mold with)

Flow Pattern in Clog Nozzle and Mold

- **Nozzle swirl** shows *clockwise* or *counter-clockwise* directions with ~3sec time intervals: direction change phenomena well-matches with the measurement[15]
- **Asymmetric flow pattern** is induced between left/right NF and between IR/OR in the mold, by nozzle clogging (unbalanced double-roll pattern).
- With clogged nozzle, surface flow from right side cross the surface and suppress the uprising flow from left NF
Jet Velocity Histories in the Nozzle and Mold

- Faster jet flow with more velocity fluctuations from non-clogged nozzle port.
- High-frequency high-amplitude jet flow from non-clogged port and low-frequency low-amplitude from clogged port.

<table>
<thead>
<tr>
<th></th>
<th>Average (m/sec)</th>
<th>Standard deviation (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>1.41</td>
<td>0.42 : 29.8 % of Avg</td>
</tr>
<tr>
<td>P2</td>
<td>0.71</td>
<td>0.30 : 42.3 % of Avg</td>
</tr>
<tr>
<td>P3</td>
<td>0.50</td>
<td>0.13 : 26.0 % of Avg</td>
</tr>
<tr>
<td>P4</td>
<td>0.14</td>
<td>0.07 : 50.0% of Avg</td>
</tr>
</tbody>
</table>

Surface Flow Patterns with Clog Nozzle

- With a clogged left port, the stronger surface flow from the right side overcomes flow from the left side.
- Vortices near SEN, starting at interface
Oil Volume Fraction at Plane 1, 4, 5

- Oil layer at right side (non-clogged nozzle port side) becomes thinner with higher surface flow.
- Oil layer on center-middle plane is thinner than other regions (near IR, OR) due to higher surface velocity.

Oil Volume Fraction at Plane 6-8

- Transient asymmetric surface flow between IR and OR produces non-uniform oil layer thickness.
- Oil layer thickness decreases towards NF, especially in center region between IR and OR.
Oil Volume Fraction at Plane 10-12

Higher surface flow from right side seems to drag oil layer (from the interface between oil and water) into water pool.

Surface Velocity Histories and Oil Entrainment

- Entrainment is induced by momentum accumulation (dependent on critical surface velocity and its duration) on oil layer.
- Thus, large entrainment follows after small entrainment. This trend is revealed from both the experiment and the LES coupled with VOF.
3D-View of Oil Entrainment Phenomena by Time

- For ~4 and ~7 sec, oil entrainments occur with higher surface velocity over ~0.18 m/sec.
- LES coupled with VOF model results (oil/water interface motion, oil entrainment, critical surface velocity for entrainment), show good agreements with those of water model experiments.

Summary

- 3D-VOF LES model was applied to predict surface motion and entrainment in 1/3-scale oil/water model with clogged nozzle.
- The model captures transient nozzle swirl and asymmetric mold flow between left/right NF and between IR/OR, by nozzle clogging.
- Transient asymmetric surface flows produce non-uniform oil layer thickness between left/right NF and IR/OR.
- Oil layer becomes thinner with higher surface flow.
- Abnormal fast surface flow towards SEN drags oil finger into water; then cuts off the entrained oil.
- Entrainment is induced by momentum accumulation (dependent on critical surface velocity and its duration) on oil layer: large entrainment follows after small entrainment. This trend is revealed from both the experiment and the LES coupled with VOF.
- The predictions (oil/water interface motion, oil entrainment, critical surface velocity for entrainment), show good agreement with the water model experiments and indicate excellent potential of the LES model to predict slag/steel interface motion and slag entrainment in a mold of real caster.
Acknowledgments

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References