Bubble Formation, Breakup and Coalescence in Stopper-rod Nozzle Flow and Effect on Multiphase Mold Flow

POSTECH: Seong-Mook Cho, Seon-Hyo Kim, Hyoung-Jun Lee, Dae-Woo Yoon

UIUC: Brian G. Thomas

Research Scope

- To gain insight of argon bubble behavior (bubble formation, breakup and coalescence) in stopper-rod nozzle and its effects on mold flow
- To evaluate Euler-Lagrange approach for predicting bubble behavior

- 1/3 scale water model experiments for visualizing argon bubble behavior in nozzle and mold and measuring level fluctuation
- Computational modeling of argon behavior in mold with Euler-Lagrange approach (Discrete Phase Model (DPM))
Schematic of 1/3 Scale Water Model

- Tundish 500mm
- Bore diameter of SEN: 25mm
- Submergence depth: 60mm
- Port angle: 35 deg downward
- Nozzle wall thickness: 10.5mm
- Water flow meter

Schematic of Stopper-rod

6 holes for injecting argon gas

- OR
- NF
- IR

<Front View>

<Cross-sectional View>
**Process Conditions**

<table>
<thead>
<tr>
<th>1/3 scale water model</th>
<th>Real process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid flow rate</td>
<td>35.0, 40.0 LPM (Water)</td>
</tr>
<tr>
<td>Casting speed</td>
<td>0.93, 1.07 m/min</td>
</tr>
<tr>
<td>Argon Gas Flow rate</td>
<td>0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6 SLPM (273K)</td>
</tr>
<tr>
<td></td>
<td>0.2, 0.4, 0.6, 0.9, 1.1, 1.3, 1.5, 1.7 LPM (298K)</td>
</tr>
<tr>
<td>Argon Gas Volume Fraction</td>
<td>0.6, 1.2, 1.8, 2.4, 3.0, 3.5, 4.0, 4.6 % (35.0 LPM)</td>
</tr>
<tr>
<td></td>
<td>0.5, 1.0, 1.6, 2.1, 2.6, 3.1, 3.6, 4.0 % (40.0 LPM)</td>
</tr>
</tbody>
</table>

- Liquid flow similarity between the 1/3 scale water model and the real caster conditions
  \[ \text{Froude number} = \frac{v}{\sqrt{gL}} \]

- Argon gas similarity between the 1/3 scale water model and the real caster conditions
  \[ \text{Argon gas volume fraction} = \frac{\text{Argon gas volume flow rate (at 298K)} \times 100}{\text{Water volume flow rate + Argon gas volume flow rate (at 298K)} \times 100} \]

**Visualizing Bubble Behavior**

- Recording high speed videos
- Analyzing videos and snap shots

“Recording area”
- \( \square \) in the SEN
- \( \bullet \), \( \bigcirc \) in the mold

“Recording information”
- \( \bullet \) ~ \( \square \): 1900fps, 512 x 384
- \( \bigcirc \), \( \bullet \): 1200fps, 640 x 480
Measuring Surface Level Fluctuation

< Measuring positions of surface level >
- Measure surface level with ultrasonic displacement 3 sensors
- Compare level profiles on 1/8, 1/4, 3/8 points between right and left NF
- Calculate average level, standard deviation of level
- Transfer level fluctuation profiles to power spectrum by FFT (Fast Fourier Transform) analysis

Specifications

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Ultrasonic displacement sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response time</td>
<td>20Hz</td>
</tr>
<tr>
<td>Collecting data frequency</td>
<td>1Hz</td>
</tr>
<tr>
<td>Collecting data time</td>
<td>1000 sec</td>
</tr>
<tr>
<td>Sensor head dimension</td>
<td>30 mm</td>
</tr>
<tr>
<td>Measuring direction</td>
<td>Vertical direction to sensor head</td>
</tr>
</tbody>
</table>

Mechanism of Argon Bubble Formation

<Snap Shot of Initial Behavior of Bubbles>

<Initiation> <Expansion> <Elongation> <Detachment>

Sometimes, small bubble remains

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Effect of Liquid and Argon Flow Rate on Active Holes

- Argon gas flow rate affect on the number of activated gas holes
- There is the threshold of argon gas flow rate for activating gas hole
- Minimum argon gas flow rate could be between 1.4 and 1.6 SLPM for activating all gas holes

Total Bubbling Frequency & Argon Bubble Size

- Total bubbling frequency get higher with higher argon gas injection
- Averaged bubble size get bigger with higher argon gas injection
Validation of Bai’s Model
Prediction of Argon Bubble Size

Vertical red line = measured water velocity from small bubbles in video = 0.6 m/s
Argon flow rate = 4.4 ml/s

- Measured bubble size (from video): 5 mm
- Calculated with bubbling frequency: 4.5 mm
- Predicted with Hua Bai’s analytical model: 4.3 mm

Bai’s model can be applied to predict the initial bubble size in the gas hole at stopper-rod

Bai and Thomas, MTB, Vol. 32B, 2001, p. 1143-1159

Argon Bubble Breakup near Stopper-rod tip

Average bubble diameter: ~ 4.5 mm
Maximum bubble diameter: < 1 mm

- Bubbles from the gas holes break up at the region between 1st and 2nd region (between tundish bottom and SEN inlet)
Argon Bubble Distribution through the Nozzle

- Bubbles look bigger down through the nozzle
- Perhaps: larger bubbles accumulate with time; or else bubbles coalesce

Argon Bubble Size Change near Nozzle Exit

- Bubbles smaller at nozzle bottom
- Bubbles coalesce at the top region of nozzle port (stagnant flow region)
Calculation of Maximum Bubble Diameter in the Nozzle

Critical Weber number:

\[ We_c = \frac{\rho_w (u_{w-Ar})^2 d_M}{\sigma} \left( \frac{\rho_{Ar}}{\rho_w} \right)^{1/3} \]

\[ \dot{E} = \frac{2f(u_w)^3}{D_{SEN}} \]

\[ f = 0.079 (\text{Re}_w)^{-1/4} \]

\[ \text{Re}_w = \frac{\rho_w u_w D_{SEN}}{\mu_w} \]

\[ C_1 = 2.0 \text{ (by Batchelor)} \]

\[ d_M = \left( \frac{\sigma We_c}{2} \right)^{3/5} \left( \frac{\rho_{Ar}}{\rho_w} \right)^{1/5} \left( \frac{\rho_w \dot{E}}{2} \right)^{2/5} \]

- Maximum bubble size in the stopper-rod nozzle can be predicted well by Evans’s model

Evans et al., Chemical Engineering Science, Vol. 54, 1999, p.4861-4867

Geometry, Mesh and Boundary Conditions (Nozzle Flow)

- Hexa meshes
- The number of total meshes: 0.24 million

Water: 35.0 LPM

<table>
<thead>
<tr>
<th>Water (inlet)</th>
<th>( u_w ): 1.057 m/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>1e-05 m^2/sec^2</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>1e-05 m^2/sec^3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Port outlet</th>
<th>( k ): 1e-05 m^2/sec^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon )</td>
<td>1e-05 m^2/sec^3</td>
</tr>
</tbody>
</table>
Stopper-rod Nozzle Flow

“Velocity magnitude”

“Turbulent kinetic energy”

“Turbulent kinetic energy Dissipation rate”

Calculated Turbulent Kinetic Energy Dissipation Rate & Argon Bubble Breakup

- Nozzle flow with high turbulent kinetic energy dissipation rate breaks bubbles up

Bubble breakup

Bubble coalescence

Bubble breakup
Transport of Argon Bubbles: Lagrange Discrete Phase Model (DPM)

- The model assumption: low (<10%) volume fraction of the dispersed phase (argon)

\[
\frac{du_{Ar}}{dt} = F_D(u - u_{Ar}) + \frac{(\rho_{Ar} - \rho)}{\rho_{Ar}} \frac{d}{dt}(u - u_{Ar}) + \frac{\rho}{\rho_{Ar}} \frac{d}{dt}(u_{Ar}) + \frac{\rho}{\rho_{Ar}} u_{Ar} \frac{\partial u}{\partial x_i}
\]

- Force balance on argon bubble

\[
F_D = \frac{18\mu}{\rho_{Ar} d_{Ar}^3} \frac{C_D Re}{24} \quad \text{Re} = \frac{\rho d_{Ar} |u_{Ar} - u|}{\mu}
\]

- Drag force
- Gravity force
- Virtual mass force
- Pressure gradient force

\[ u : \text{water velocity} \]
\[ u_{Ar} : \text{argon velocity} \]
\[ \mu : \text{molecular viscosity of water} \]
\[ \rho : \text{water density} \]
\[ \rho_{Ar} : \text{argon density} \]
\[ d_{Ar} : \text{argon bubble diameter} \]

- Virtual mass force: the force required to accelerate the fluid surrounding the particle

- Numerical method: Two-way turbulence coupling

Continuous phase (Water) flow field calculation

Discrete phase (Argon bubble) trajectory calculation

continuous phase source terms calculation

\[ S_{mm,Ar} = (F_D + F_C + F_v + F_P)m_y \Delta t \]
**Argon Size Distribution for Input: Rosin-Rammler Diameter Distribution**

**Rosin-Rammler Diameter Distribution**

\[ Y_d = e^{-\frac{(d/\bar{d})}{n}} \]

- \( Y_d \): Mass fraction of particles with diameter greater than \( d \)
- \( \bar{d} \): Mean diameter
- \( n \): spread parameter

**Argon: 1.6 SLPM**

<table>
<thead>
<tr>
<th>Total flow rate</th>
<th>1.082e-05 kg/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min diameter</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Max diameter</td>
<td>2 mm</td>
</tr>
<tr>
<td>Mean diameter</td>
<td>1 mm</td>
</tr>
<tr>
<td>Spread parameter</td>
<td>3.5</td>
</tr>
<tr>
<td>Number of diameters</td>
<td>20</td>
</tr>
</tbody>
</table>

### Mass fraction of argon bubbles (>d)

- **Argon bubble diameter (mm)**: 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0

### Mass fraction

<table>
<thead>
<tr>
<th>Argon bubble diameter (mm)</th>
<th>0.00</th>
<th>0.05</th>
<th>0.10</th>
<th>0.15</th>
<th>0.20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass fraction</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

### The number of bubbles (#/sec)

<table>
<thead>
<tr>
<th>Argon bubble diameter (mm)</th>
<th>0</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
<th>3500</th>
<th>4000</th>
<th>4500</th>
<th>5000</th>
<th>5500</th>
<th>6000</th>
</tr>
</thead>
<tbody>
<tr>
<td>The number of bubbles</td>
<td></td>
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**Argon Distribution in the Mold**

**Water: 35.0 LPM, Argon: 1.6 SLPM**

- With Lagrange model (DPM), argon distribution in the mold is well predicted;
- argon floating region at the surface and argon penetration depth into mold inner region

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[Image of mold distribution with Argon concentration]
Mold Flow Pattern with Argon Injection

- After argon injection, classic double roll pattern is changed to complex flow pattern; By buoyancy force induced by argon bubbles
- Surface flow near SEN goes up to the surface; this could induces more severe level fluctuation

Argon Effect on Surface Level & Fluctuation: Measurement

With more argon gas injecting
- Greater surface level difference between SEN and NF
- Severe level fluctuation at the region near SEN, but Smaller level fluctuation at the others
Argon Effect on Surface Level Power Spectrum

- Level fluctuation near SEN show more power than other regions
- With 1.6 SLPM of gas flow rate, power difference between nozzle and NF is quite severe in the frequency range bigger than 0.05Hz

Summary

- **Bubble behavior in the nozzle**
  - Initial bubble is expanded, elongated and detached from stopper-rod tip
  - Bubbles breakup due to shear in region of high velocity gradient / turbulent dissipation in stopper/nozzle gap and perhaps also in nozzle well bottom
  - Bubble size distribution entering mold is smaller than initial size at stopper
  - Bubbles coalesce in recirculation regions, such as top of nozzle port

- **Bubble behavior in the mold**
  - Argon bubble floating up affect the flow pattern, resulting in complex double roll pattern
  - These bubbles disrupt surface where they exit near SEN, and thus more surface level fluctuations with higher gas injection

- **Euler-Lagrange coupled multiphase flow model can simulate the mold flow pattern, bubble distribution, and the surface level fluctuation effects.**
Acknowledgements

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