Continuous Casting Consortium

MechSE

ANNUAL REPORT 2012

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

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Continuous Casting Consortium

Research Scope

- Objectives:

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

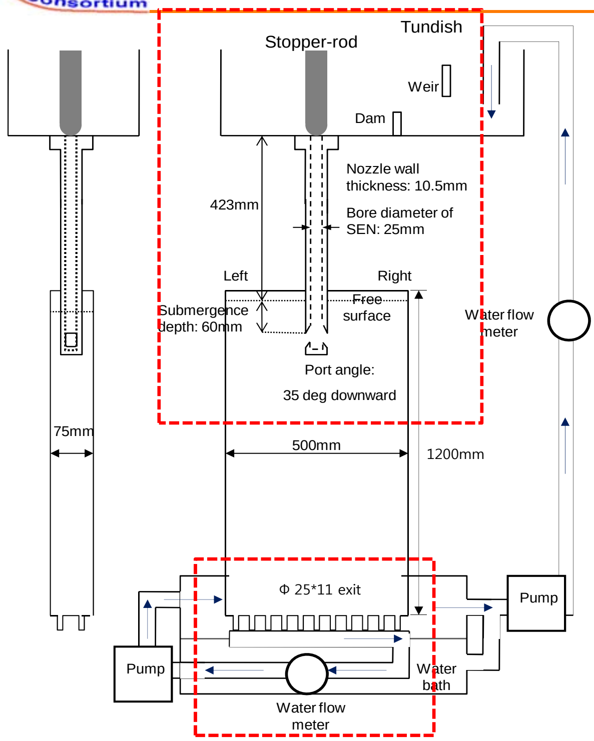
  - To evaluate Euler-Lagrange approach for predicting bubble behavior

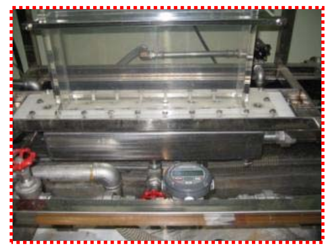
- Methodologies:

  - 1/3 scale water model experiments for visualizing argon bubble behavior in nozzle and mold and measuring level fluctuation

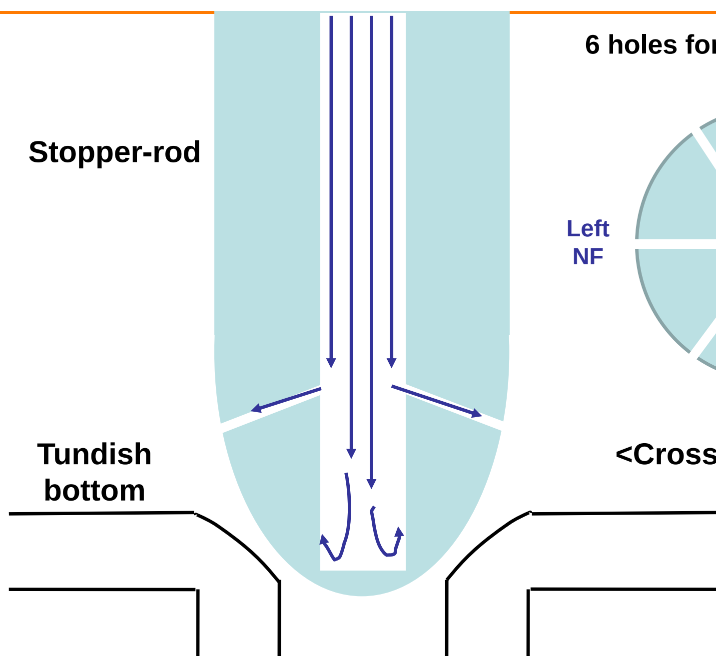
  - Computational modeling of argon behavior in mold with Euler-Lagrange approach (Discrete Phase Model (DPM))

Schematic of 1/3 Scale Water Model



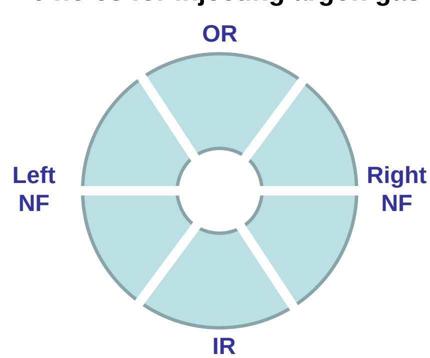


Schematic of Stopper-rod



<Front View>

6 holes for injecting argon gas



<Cross-sectional View>

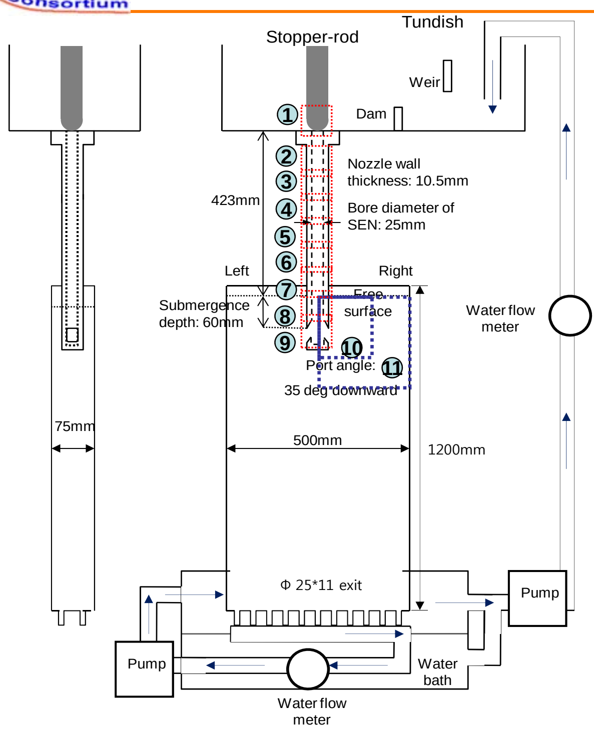
Process Conditions

	1/3 scale water model	Real process
Mold (width x thickness)	500mm x 75 mm	1500mm x 225 mm
Liquid flow rate	35.0, 40.0 LPM (Water)	545.6, 623.5 LPM (Steel)
Casting speed	0.93, 1.07 m/min	1.61, 1.85 m/min
Argon Gas Flow rate	0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6 SLPM (273K) 0.2, 0.4, 0.6, 0.9, 1.1, 1.3, 1.5, 1.7 LPM (298K)	0.8, 1.7, 2.5, 3.3, 4.2, 5.0, 5.8, 6.7 SLPM (273K) 3.3, 6.6, 9.9, 13.2, 16.4, 20.0, 23.0, 26.2 LPM (1873K)
Argon Gas Volume Fraction	0.6, 1.2, 1.8, 2.4, 3.0, 3.5, 4.0, 4.6 % (35.0 LPM) 0.5, 1.0, 1.6, 2.1, 2.6, 3.1, 3.6, 4.0 % (40.0 LPM)	0.6, 1.2, 1.8, 2.4, 3.0, 3.5, 4.0, 4.6 % (545.6 LPM) 0.5, 1.0, 1.6, 2.1, 2.6, 3.1, 3.6, 4.0 % (623.5 LPM)

- ❑ Liquid flow similarity between the 1/3 scale water model and the real caster conditions
  - ➡ Froude number (Ratio of Inertia force to gravitational force) = $v / \sqrt{gL}$
- ❑ Argon gas similarity between the 1/3 scale water model and the real caster conditions
  - ➡ Argon gas volume fraction (%)

$$\frac{\text{Argon gas volume flow rate (at 298K) X 100}}{\text{Water volume flow rate + Argon gas volume flow rate (at 298K)}} = \frac{\text{Argon gas volume flow rate (at 1873K) X 100}}{\text{Steel volume flow rate + Argon gas volume flow rate (at 1873K)}}$$

Visualizing Bubble Behavior



- ❑ Recording high speed videos
- ❑ Analyzing videos and snap shots

"Recording area"

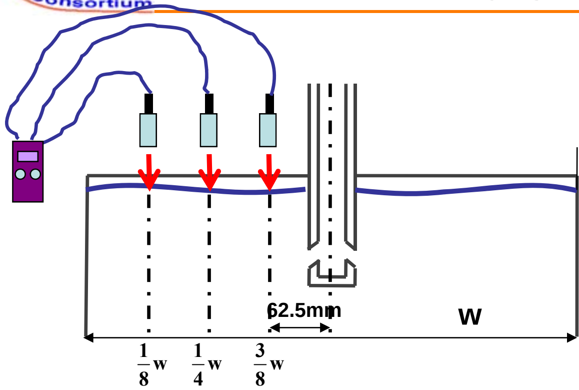
- ⬚ : ① ~ ⑨ in the SEN
- ⬚ : ⑩ , ⑪ in the mold

"Recording information"

① ~ ⑨: 1900fps, 512 x 384

⑩, ⑪ : 1200fps, 640 x 480

Measuring Surface Level Fluctuation



< Measuring positions of surface level>

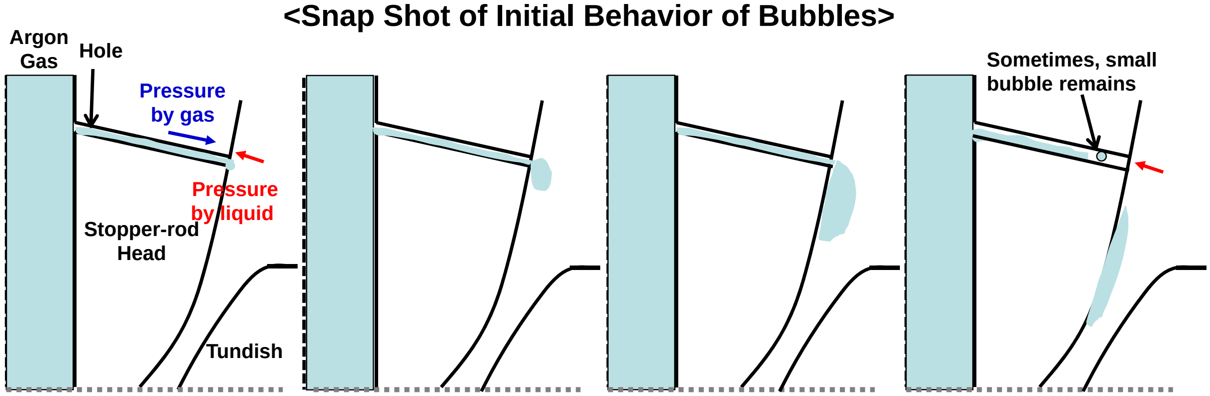
- Measure surface level with ultrasonic displacement 3 sensors
- Compare level profiles on 1/8, 1/4, 3/8 points between right and left NF
- Calculate average level, standard deviation of level
- Transfer level fluctuation profiles to power spectrum by FFT(Fast Fourier Transform) analysis

Specifications

	Ultrasonic displacement sensor
Response time	20Hz
Collecting data frequency	1Hz
Collecting data time	1000sec
Sensor head dimension	30mm 10mm
Measuring direction	Vertical direction to sensor head

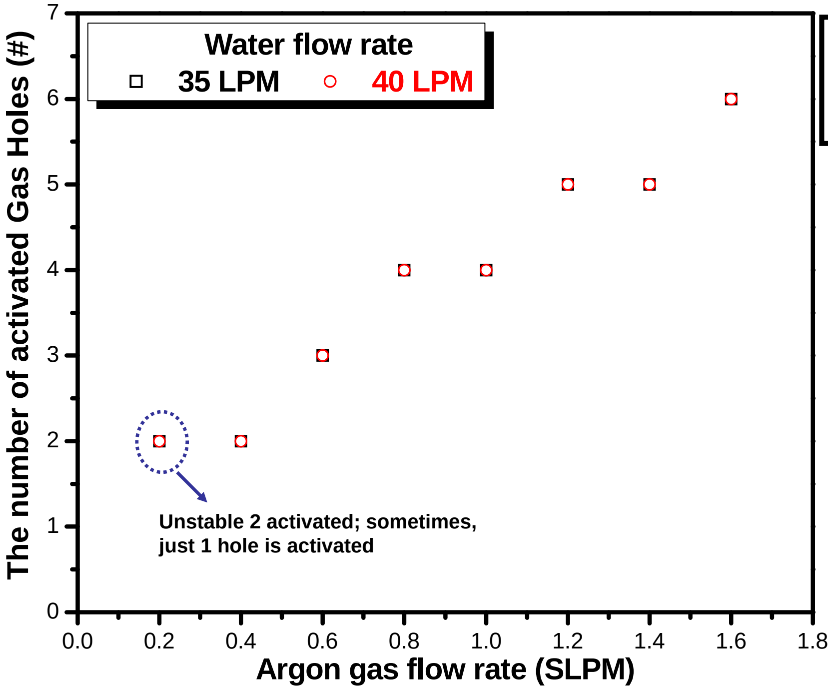
Mechanism of Argon Bubble Formation

<Snap Shot of Initial Behavior of Bubbles>



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

Effect of Liquid and Argon Flow Rate on Active Holes



Based on observations of video of 1/3 water model

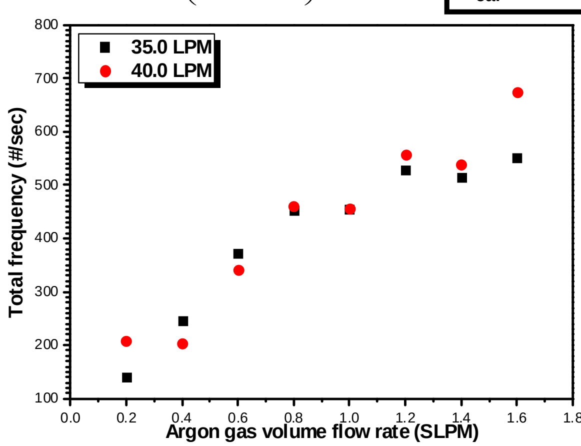
- Argon gas flow rate affect on the number of activated gas holes
- There is the threshold of argon gas flow rate for activating gas hole
- Minimum argon gas flow rate could be between 1.4 and 1.6 SLPM for activating all gas holes

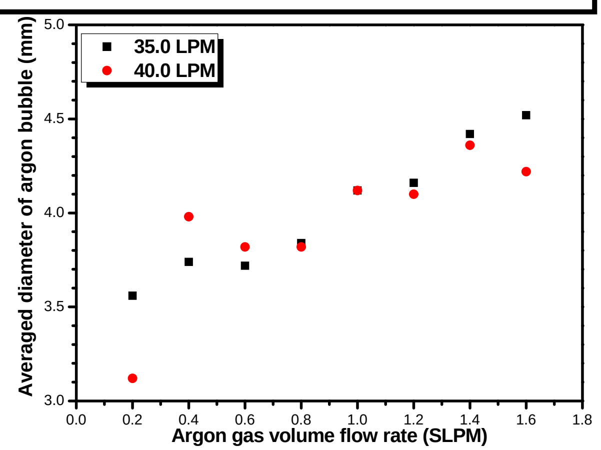
Total Bubbling Frequency & Argon Bubble Size

$$V_{bubble} = \frac{Q_{main}}{f} = \frac{4}{3}\pi\left(\frac{d_{cal}}{2}\right)^3$$

$$d_{cal} = \left(\frac{24Q_{main}}{4\pi f}\right)^{\frac{1}{3}}$$

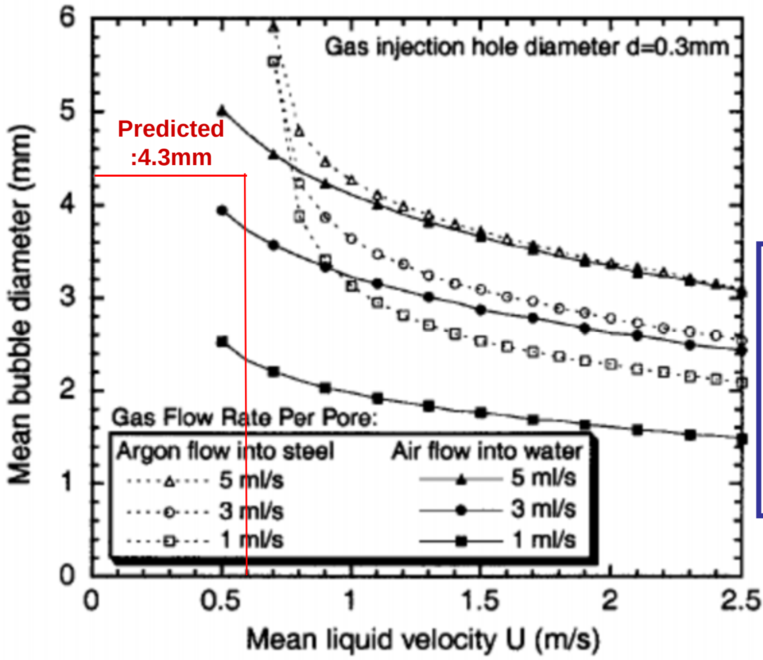
Q_{main} : total argon flow rate (mm^3/sec)
V_{bubble} : averaged bubble volume (mm^3)
f : total bubbling frequency in the six holes measured from video (#/sec)
d_{cal}: calculated average bubble diameter (mm)





- 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



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

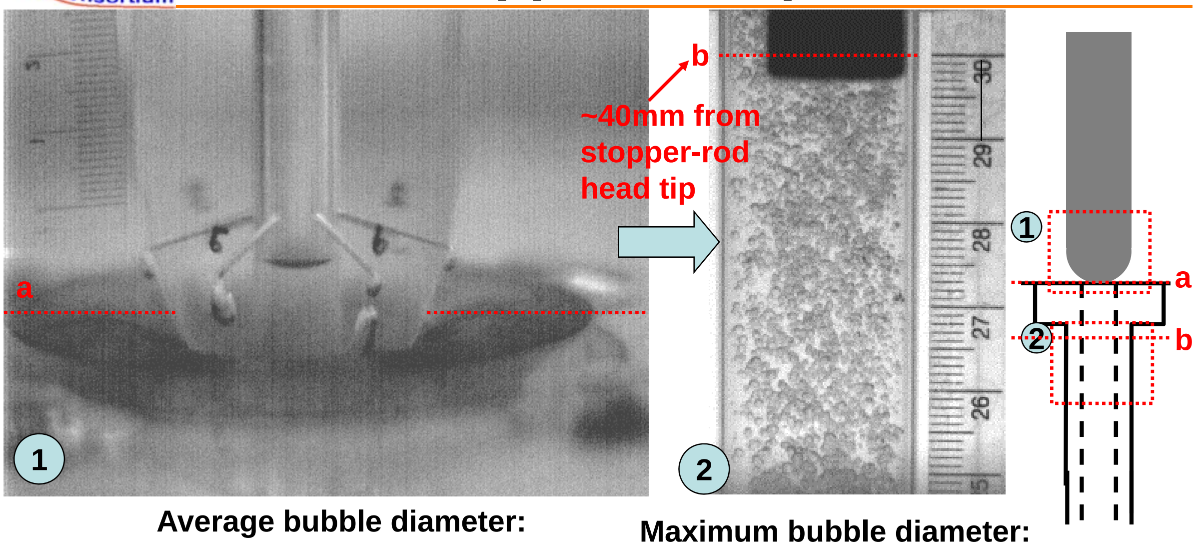
Vertical red line =
= measured water velocity from small bubbles in video
= 0.6m/s

Argon flow rate = 4.4 ml/s

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

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

Argon Bubble Breakup near Stopper-rod tip

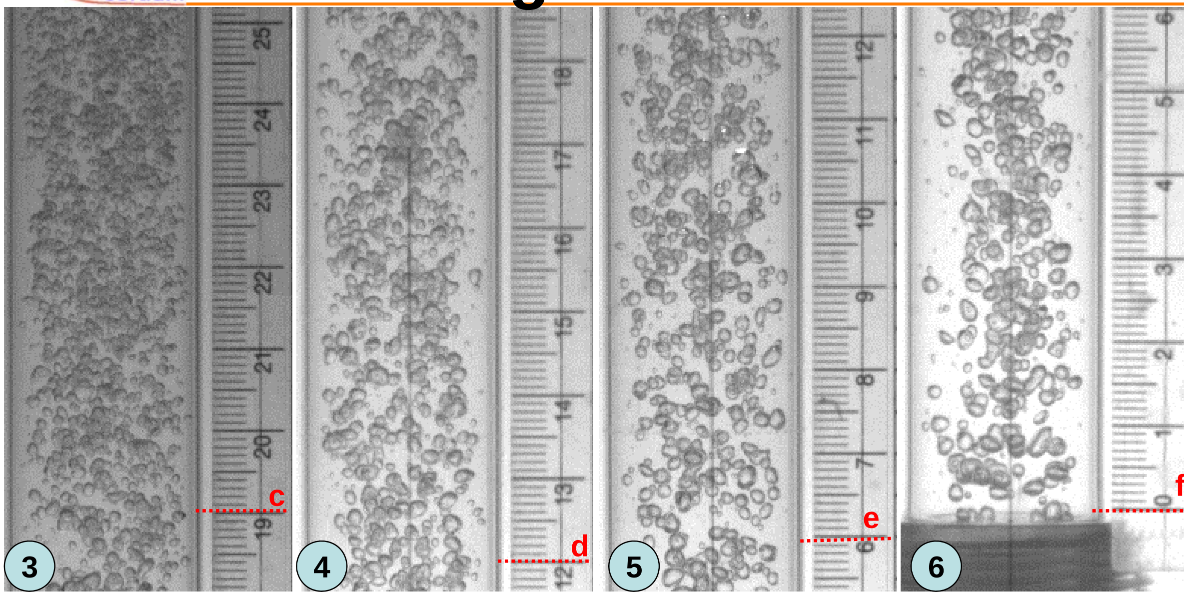


Average bubble diameter: ~ 4.5 mm

Maximum bubble diameter: < 1 mm

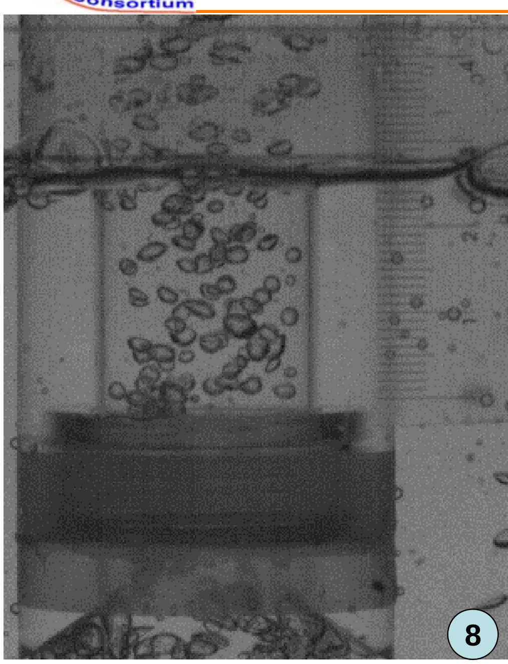
- Bubbles from the gas holes break up at the region between 1st and 2nd region (between tundish bottom and SEN inlet)

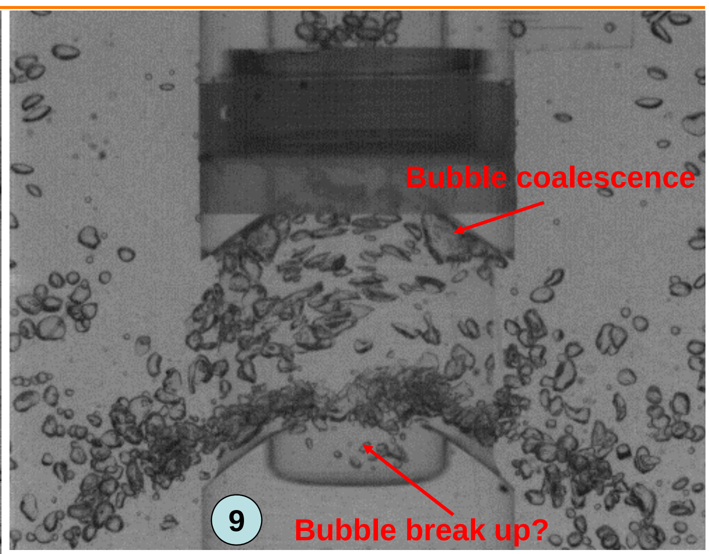
Argon Bubble Distribution through the Nozzle



- 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:

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

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

$$f = 0.079\left(Re_w\right)^{-1/4}$$

$$Re_w = \frac{\rho_w u_w D_{SEN}}{\mu_w}$$

Kolmogoroff energy distribution law:

$$\left(u_{w-Ar}\right)^2 = C_1(\dot{E} d_M)^{2/3}$$

$$C_1 \approx 2.0 \text{ (by Batchelor)}$$

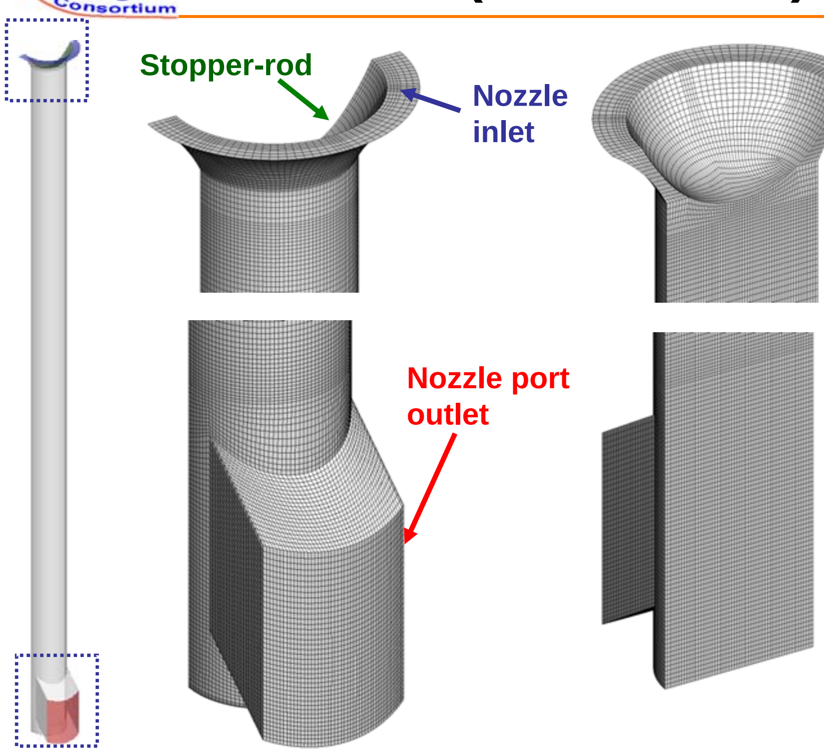
$$\boxed{d_M = \left(\frac{\sigma We_c}{2}\right)^{3/5} \left(\rho_{Ar}\right)^{-1/5} \left(\rho_w \dot{E}\right)^{-2/5}}$$

ρ_w	Water density	998.2 kg/m3
ρ_{Ar}	Argon gas density	1.623 kg/m3
μ_w	Water absolute viscosity	0.001 kg/m,sec
σ	surface tension	0.0122 N/m
D_{SEN}	SEN inner diameter	0.025 m
u_w	Water velocity	1.19 m/sec
Re_w	Water Reynolds number	2.97e+04
f	friction factor	0.006
$\dot{E}$	average energy dissipation rate / unit mass	0.808 m2 / sec3
We_c	critical Weber number	1.2
d_M	maximum diameter	0.00326 m (3.26 mm)

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

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

Geometry, Mesh and Boundary Conditions (Nozzle Flow)

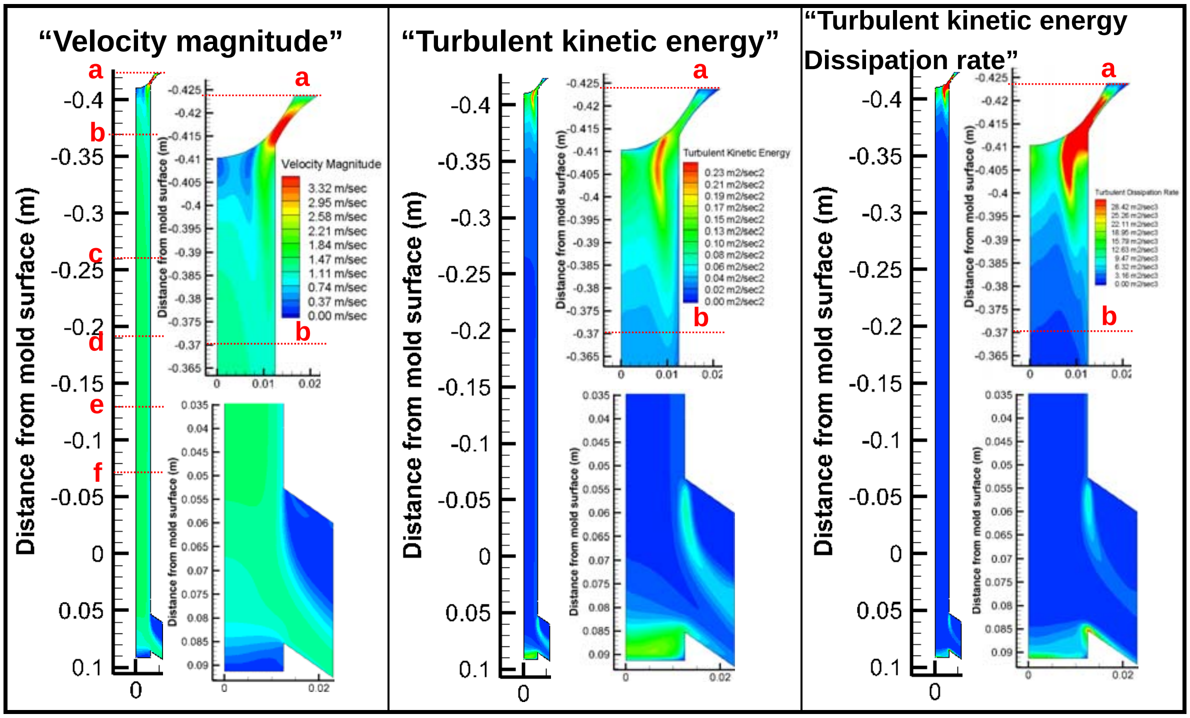


- Hexa meshes
- The number of total meshes: 0.24 million

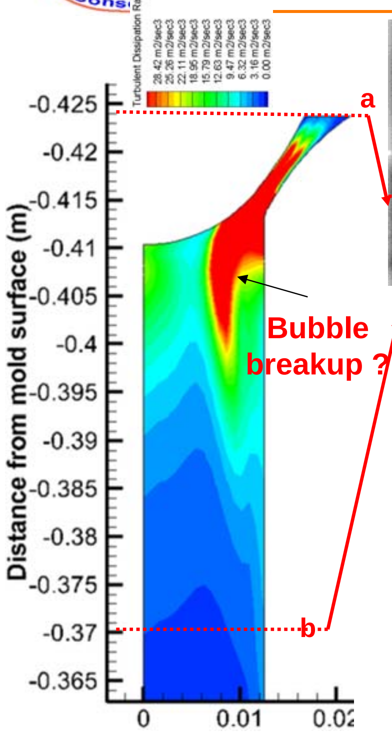
Water: 35.0 LPM

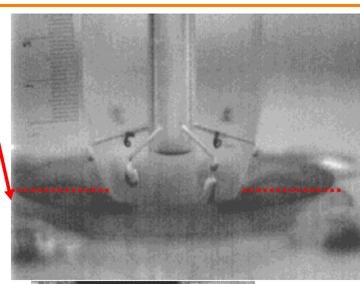
Water (inlet)	u_w: 1.057 m/sec k : 1e-05 m2/sec2 ε : 1e-05 m2/sec3
Port outlet	k : 1e-05 m2/sec2 ε : 1e-05 m2/sec3

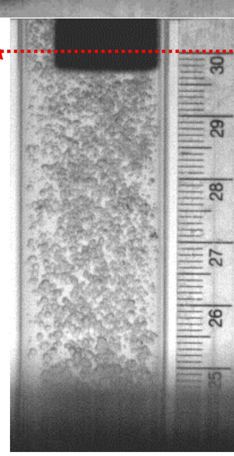
Stopper-rod Nozzle Flow



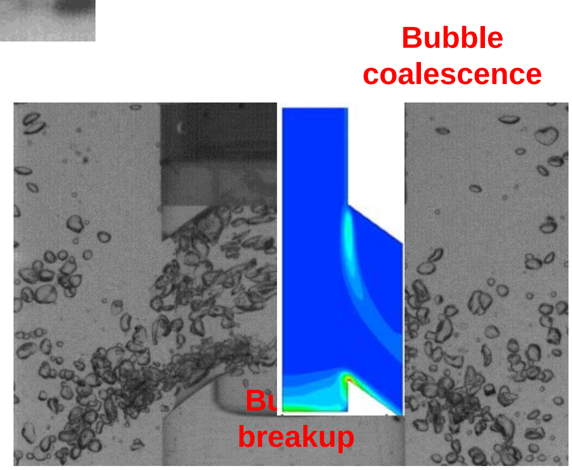
Calculated Turbulent Kinetic Energy Dissipation Rate & Argon Bubble Breakup



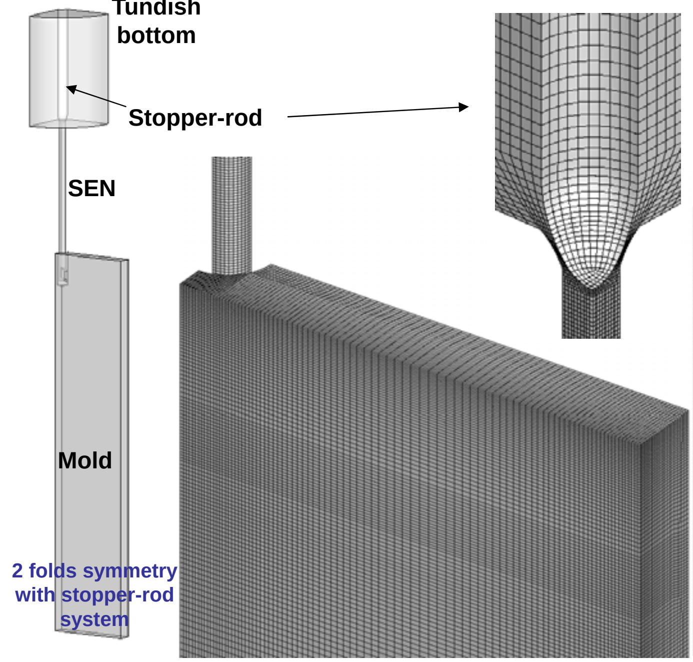




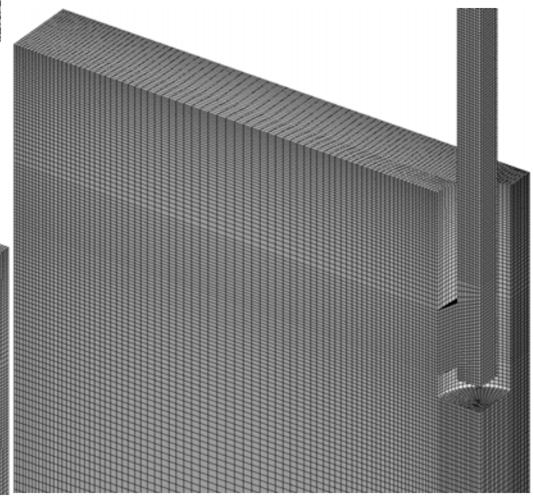
- Nozzle flow with high turbulent kinetic energy dissipation rate breaks bubbles up



Geometry, Mesh for Lagrange Model



Domain	The number of Meshes
¼ domain	0.14 million



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

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

Force balance on argon bubble

$$\frac{du_{Ar}}{dt} = \underbrace{F_D(u-u_{Ar})}_{\text{Drag force}} + \underbrace{\frac{(\rho_{Ar}-\rho)}{\rho_{Ar}}g}_{\text{Gravity force}} + \underbrace{\frac{1}{2}\frac{\rho}{\rho_{Ar}}\frac{d}{dt}(u-u_{Ar})}_{\text{Virtual mass force}} + \underbrace{\left(\frac{\rho}{\rho_{Ar}}\right)u_{Ar_i}\frac{\partial u}{\partial x_i}}_{\text{Pressure gradient force}}$$

$$F_D = \frac{18\mu}{\rho_{Ar} d_{Ar}^2}\frac{C_D Re}{24} \qquad Re = \frac{\rho d_{Ar}|u_{Ar} - u|}{\mu}$$

u : water velocity
u_{Ar} : argon velocity
μ : molecular viscosity of water
ρ : water density
ρ_{Ar} : argon density
d_{Ar} : 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

$$S_{mom,Ar} = (F_D + F_G + F_V + F_P)\, m_p\, \Delta t$$

Argon Size Distribution for Input: Rosin-Rammler Diameter Distribution

❑ Rosin-Rammler Diameter Distribution

$$Y_d = e^{-\left(d/\bar{d}\right)^n}$$

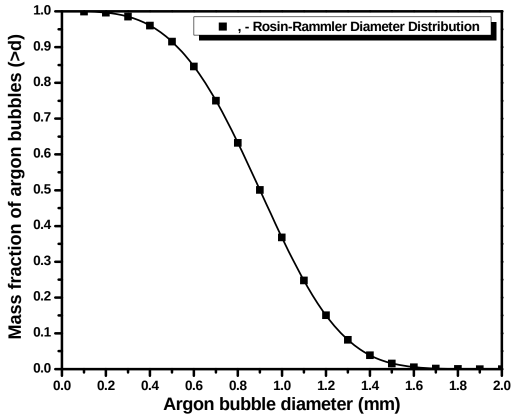
Y_d : Mass fraction of particles with diameter greater than d

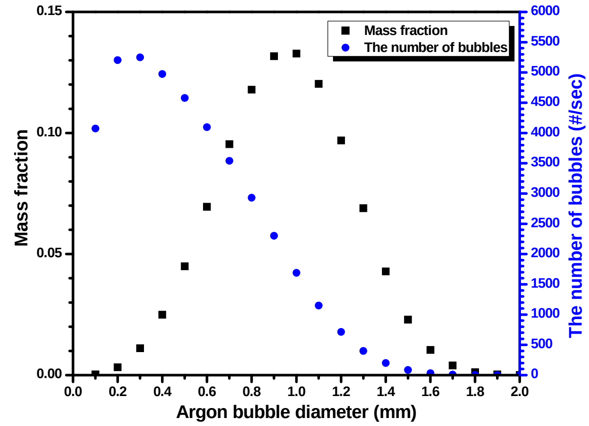
$\bar{d}$: Mean diameter

n : spread parameter

Argon: 1.6 SLPM

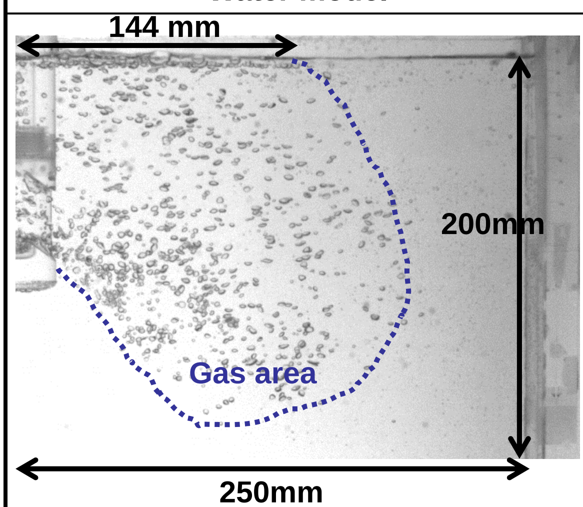
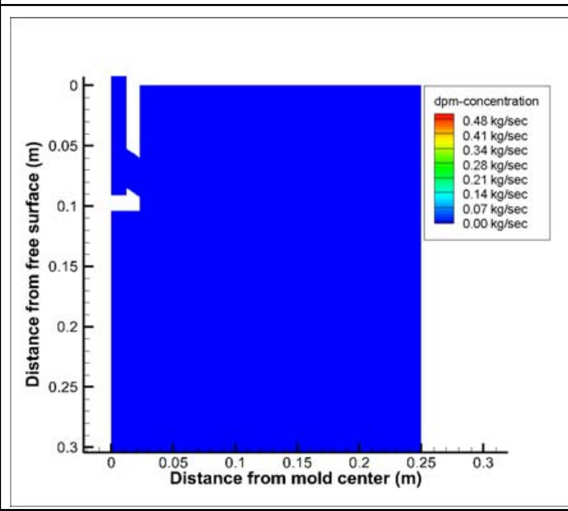
Total flow rate	1.082e-05 kg/sec
Min diameter	0.1 mm
Max diameter	2 mm
Mean diameter	1 mm
Spread parameter	3.5
Number of diameters	20





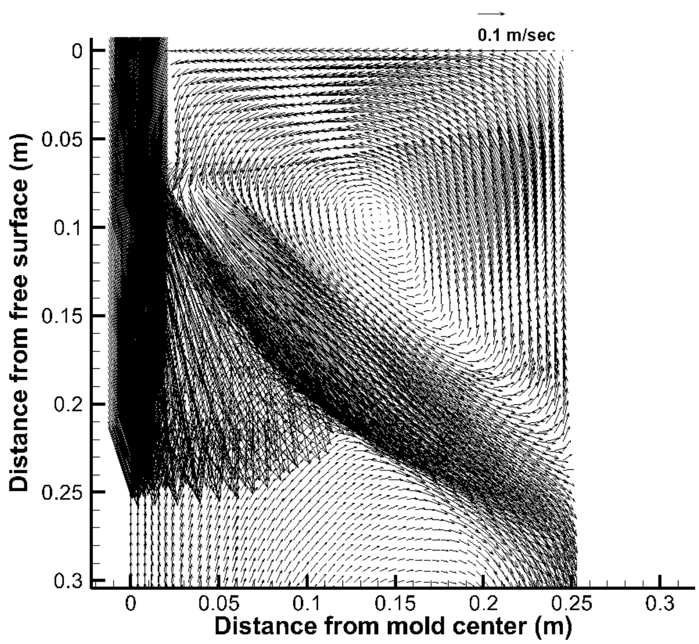
Argon Distribution in the Mold

Water: 35.0 LPM, Argon: 1.6 SLPM

Water model	Computational model
	

- 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

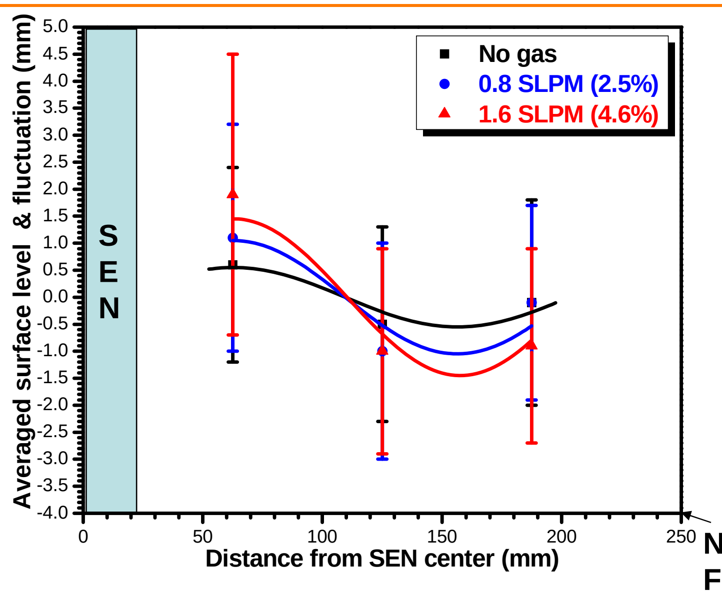
Mold Flow Pattern with Argon Injection



- 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



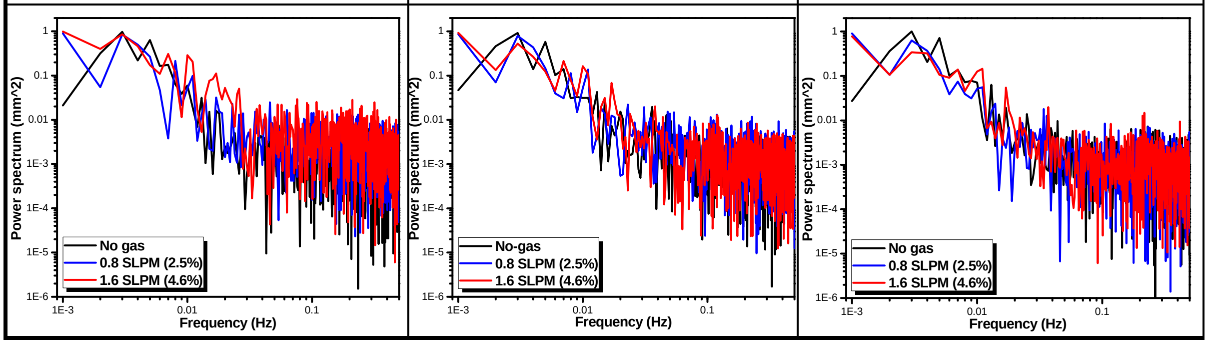
With more argon gas injecting

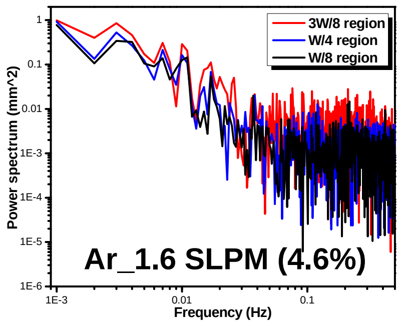
- Greater surface level difference between SEN and NF

- Severe level fluctuation at the region near SEN, but Smaller level fluctuation at the others

Argon Effect on Surface Level Power Spectrum

3W/8 (near SEN)	W/4	W/8 (near NF)





- 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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