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Clogging Effects on Asymmetric Flow and Vortex Formation

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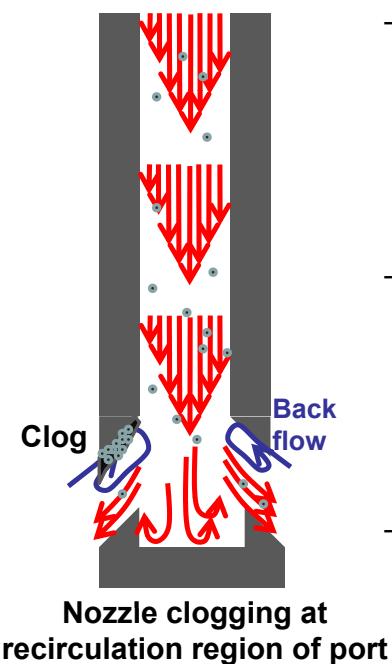
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Research Scope



- Nozzle clogging influences asymmetric flow causing problems:
 - Vortex formation:** can entrap mold flux and cause defects in slab caster
 - Level fluctuation near NFs:** disturbs the formation of the initial solidifying shell
- Objective: studying effect of asymmetric flow caused by nozzle clogging on:
 - mold flow pattern (computational model)
 - surface velocity
 - vortex formation frequency
 - level fluctuation
- Methodology:
 - water model experiments** to quantify surface flow, vortex formation and level fluctuation
 - computational model** to explain the flow pattern.

Previous Works

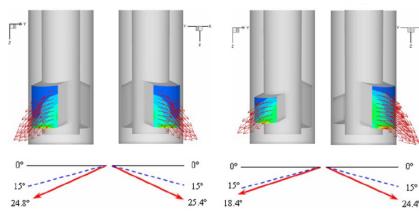


Fig. 1—Turbulence dissipation rate, velocity, and outflow angle at SEN output. Outputs under (a) nonclogged and (b) left-side clogged conditions. (Dashed angle is outlet structure angle; solid angle is jet angle at SEN output)

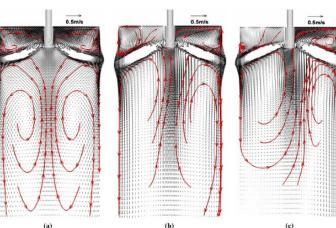


Fig. 2—Fluid flow pattern in the mold region: (a) mirror of half mold calculation, (b) full mold calculation without clogging, and (c) full mold calculation with clogging at SEN left output.

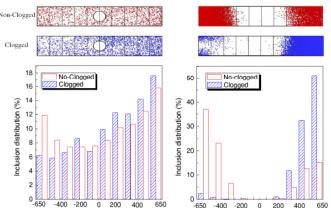


Fig. 10—Distribution of 50- μm inclusions on the top and bottom of the mold region (2.55-m long).

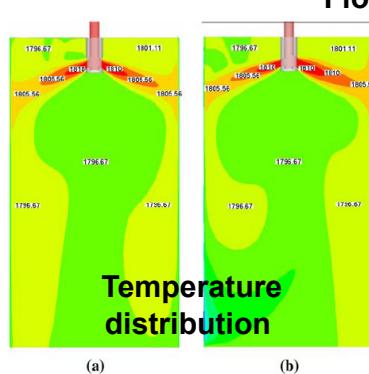


Fig. 17—Temperature distribution at the center face of the mold (K): (a) nonclogged and (b) clogged.

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Flow pattern

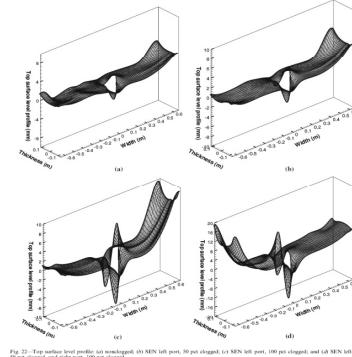


Fig. 21—3D surface level profile: (a) SEN left port, 50-pc clogged; (b) SEN left port, 100-pc clogged; and (c) SEN left port, 50-pc clogged, and (d) SEN left port, 100-pc clogged.

Particle motion

“ Lifeng Zhang, Yufeng whang and Xiangjun zuo
MTB, 2008, Vol. 39B , p534~550”

Top surface level profile

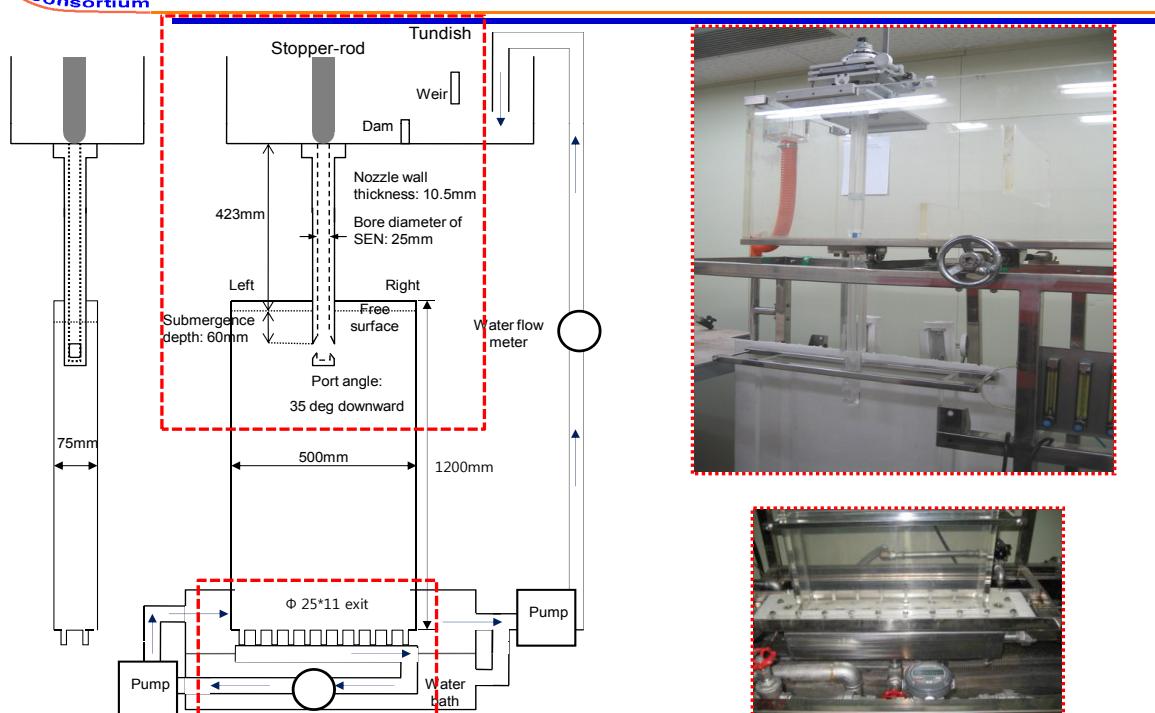
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Present research:
more detailed study
of transient surface
flow phenomena
with nozzle clogging

Schematic of 1/3 Scale Water Model



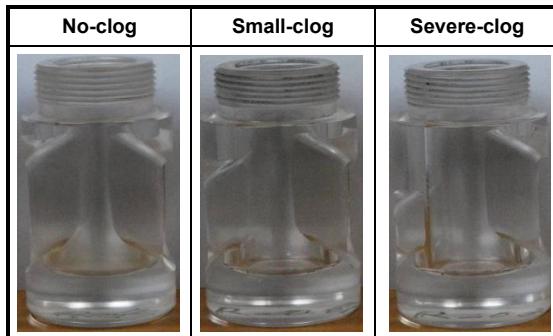
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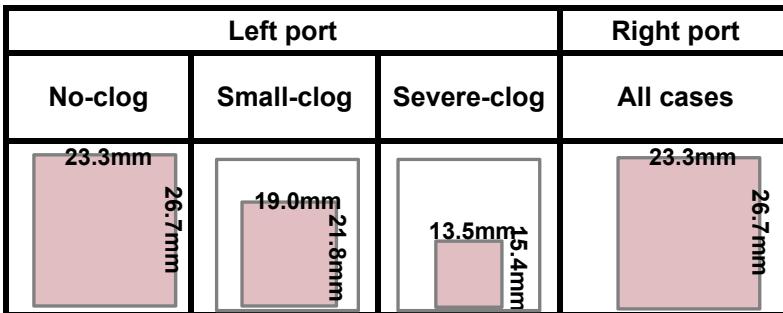
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3 Nozzles to Study Clogging Effects



Dimension of nozzle port		No-clog	Small-clog	Severe-clog
Right	Width (mm)	23.3	23.3	23.3
	Height (mm)	26.7	26.7	26.7
Left	Width (mm)	23.3	19.0	13.5
	Height (mm)	26.7	21.8	15.4
<i>Ratio of area between left and right</i>		1	0.67	0.33
<i>Ratio of area between two ports and nozzle bore</i>		2.54	2.11	1.69
Port angle (degree)		-35	-35	-35



Clog in left nozzle port

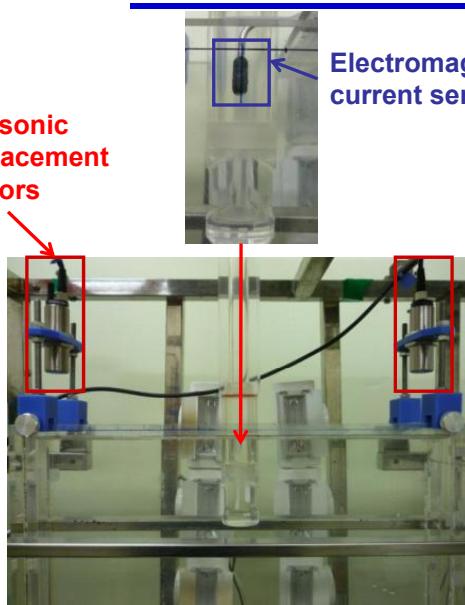
- Small-clog (33% clog)
- Severe-clog (67% clog)

Processing Conditions for Experimental and Computational Works

	1/3 scale water model	Real caster
Casting speed	0.917 m/min	1.59 m/min
Water flow rate	34.4 LPM	537 LPM (3.77 Ton/min)
Mold width	500 mm	1500 mm
Mold thickness	75 mm	225 mm
Computational mold domain	width	250 mm(No-clog), 500mm (Clog)
	thickness	37.5 mm
	length	1200 mm
SEN depth	60 mm	180 mm
ρ_{fluid}	998.2 kg/m ³ (water)	7020 kg/m ³ (steel)
μ_{fluid}	0.001003 kg/m-s (water)	0.0067 kg/m-s (steel)
Distance from closed stopper-rod to opened one (mm)	No-clog: 3.0 Small-clog: 3.1, Severe-clog: 3.2	
Nozzle (well-bottom type) port angle	35 degree	
Nozzle ports	No-clog: Symmetric ports Small-clog: 0.67_asymmetric left port, Severe-clog: 0.33_asymmetric left port	
Nozzle bore diameter (inner/outer)	25 mm/46 mm	75mm/138mm
Shell	no	Yes
Gas injection	no	Yes

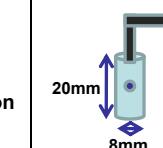
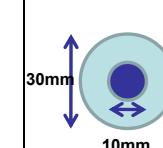
Sensors for Measurements

Ultrasonic
displacement
sensors



Electromagnetic
current sensor

Specifications

	Electromagnetic current sensor	Ultrasonic displacement sensor
Response time	1Hz	20Hz
Collecting data frequency	1Hz	1Hz
Collecting data time	1000sec	1000sec
Sensor head dimension		
Measuring direction	X,Y vector components	Vertical direction to sensor head

< Sensors in water model >

- 1 Electromagnetic current sensor for measuring surface flow velocity

- 2 Ultrasonic displacement sensors for measuring level fluctuations

Computational Model

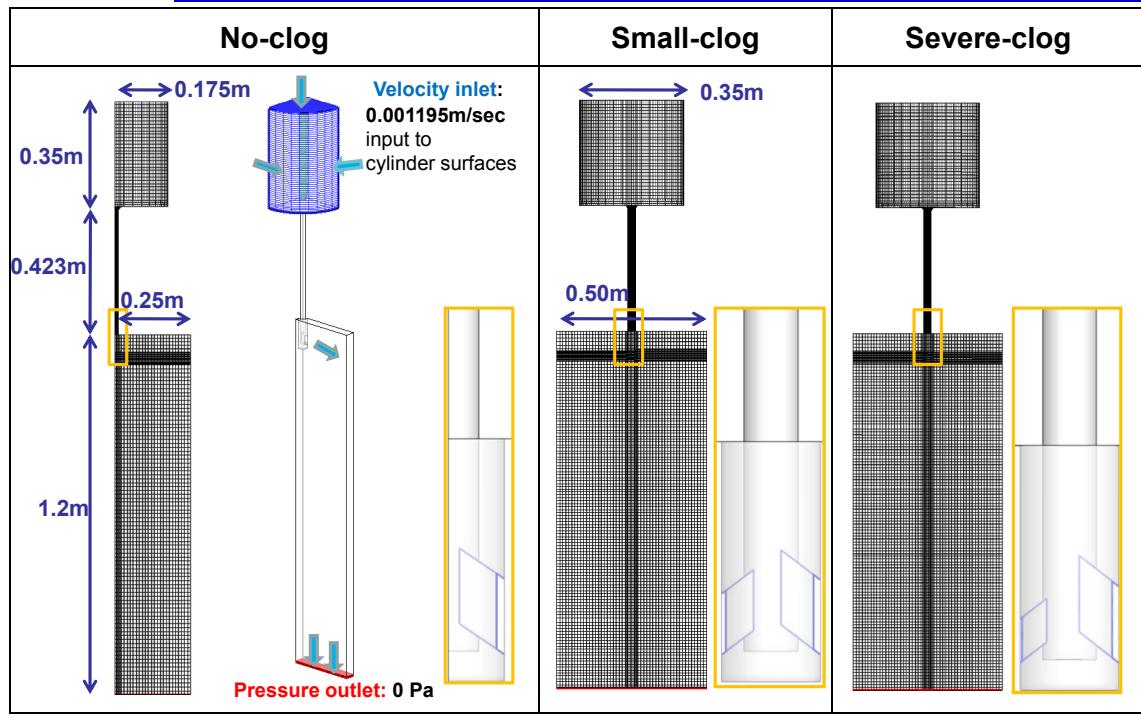
- Single-phase flow

- ✓ Steady-state, 3-D and incompressible Navier-Stokes equations for momentum conservation
- ✓ Standard $\kappa - \epsilon$ turbulence model for simulating time-averaged turbulent fluid flow
- ✓ Using Fluent

- Domain and convergence

- ✓ 1/3 scale water model geometry
- ✓ Combined computational domain of nozzle and mold assuming symmetrical flow (no-clog: quarter domain, clog: half domain)
- ✓ Hexa-cells used in the computational domain to model turbulent nozzle and mold flow (no-clog: 0.107 million, small-clog: 0.205 million, severe-clog: 0.203 million)
- ✓ Convergence in almost all cases until scaled residuals were reduced to stable 10^{-4}

Geometry, Mesh and Boundary Conditions



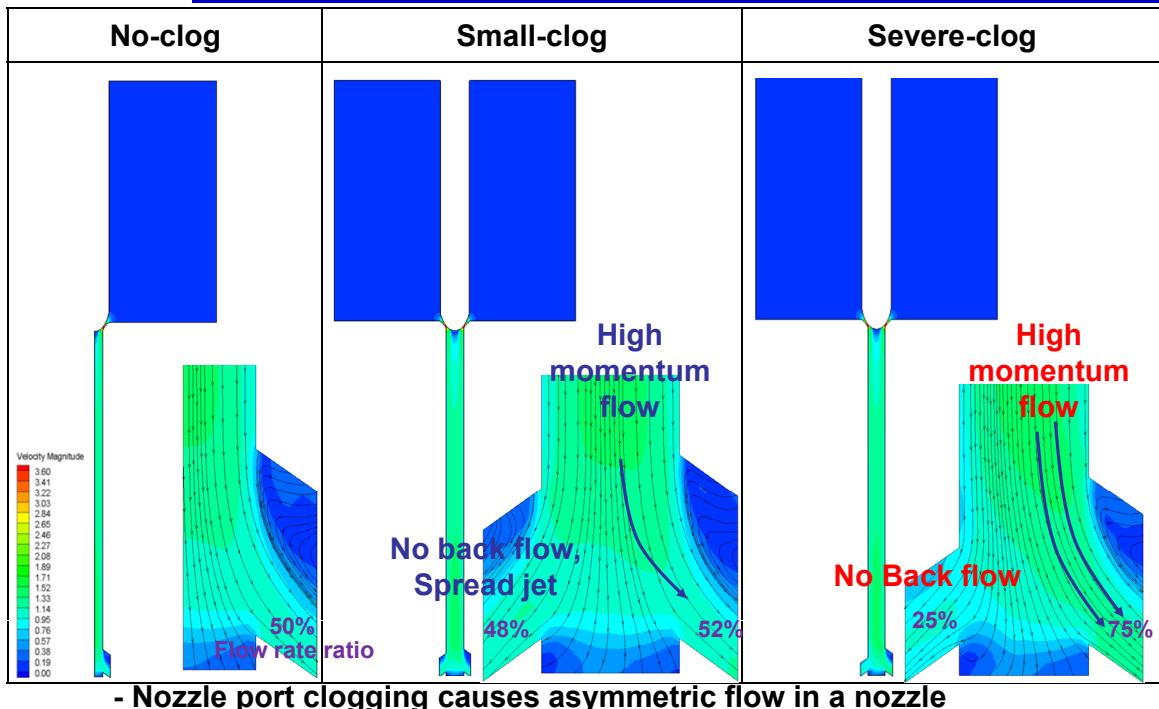
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Asymmetric Flow in the SEN with Nozzle Clogging



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Equations to Calculate Jet Characteristics



Weighted average velocity of each component

$$\bar{u}_l = \frac{\sum_{i \text{ (if outflow)}} [(u_l)_i U_i(\Delta y)_i (\Delta z)_i (f_l)_i]}{\sum_{i \text{ (if outflow)}} [U_i(\Delta y)_i (\Delta z)_i (f_l)_i]} \quad \bar{v}_l = \frac{\sum_{i \text{ (if outflow)}} [(v_l)_i U_i(\Delta y)_i (\Delta z)_i (f_l)_i]}{\sum_{i \text{ (if outflow)}} [U_i(\Delta y)_i (\Delta z)_i (f_l)_i]} \quad \bar{w}_l = \frac{\sum_{i \text{ (if outflow)}} [(w_l)_i U_i(\Delta y)_i (\Delta z)_i (f_l)_i]}{\sum_{i \text{ (if outflow)}} [U_i(\Delta y)_i (\Delta z)_i (f_l)_i]}$$

Vertical jet angle (degree)

$$\theta_{yx} = \tan^{-1}\left(\frac{\bar{v}_l}{\bar{u}_l}\right) = \tan^{-1}\left(\frac{\sum_{i \text{ (if outflow)}} [(v_l)_i U_i(\Delta y)_i (\Delta z)_i (f_l)_i]}{\sum_{i \text{ (if outflow)}} [(u_l)_i U_i(\Delta y)_i (\Delta z)_i (f_l)_i]}\right) \quad \text{average jet speed} \quad U_{jet} = \sqrt{(\bar{u}_l)^2 + (\bar{v}_l)^2 + (\bar{w}_l)^2}$$

Weighted average turbulent kinetic energy

$$\bar{K} = \frac{\sum_{i \text{ (if outflow)}} [K_i U_i(\Delta y)_i (\Delta z)_i (f_l)_i]}{\sum_{i \text{ (if outflow)}} [U_i(\Delta y)_i (\Delta z)_i (f_l)_i]}$$

Weighted average turbulent kinetic energy dissipation rate

$$\bar{\epsilon} = \frac{\sum_{i \text{ (if outflow)}} [\epsilon_i U_i(\Delta y)_i (\Delta z)_i (f_l)_i]}{\sum_{i \text{ (if outflow)}} [U_i(\Delta y)_i (\Delta z)_i (f_l)_i]}$$

Back flow zone fraction

$$\eta = \frac{\sum_{all \ i} [(\Delta y)_i (\Delta z)_i] - \sum_{i \text{ (if outflow)}} [(\Delta y)_i (\Delta z)_i]}{\sum_{all \ i} [(\Delta y)_i (\Delta z)_i]}$$

" Hua Bai and Brian G. Thomas,
MTB, 2001, Vol. 32B , No. 2"

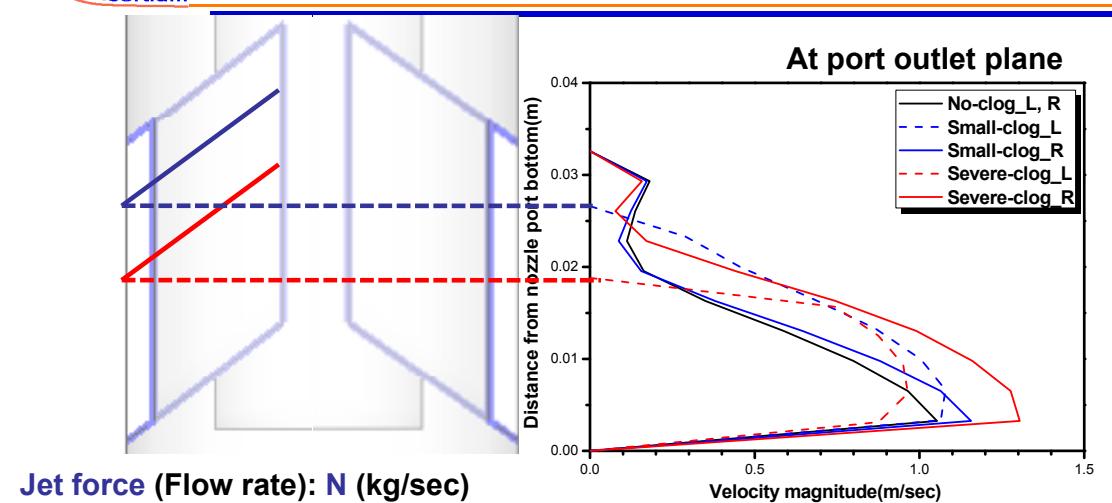
$F_{jet} \text{ (Jet Force)} = U_{jet} \text{ (Averaged Jet Speed)} \times Q_{jet} \text{ (Flow Rate)}$



Jet Characteristics

	No-clog		Small-clog		Severe-clog	
	Left	Right	Left	Right	Left	Right
Weighted average nozzle port velocity in x-direction (Outward) (m/sec)	0.450	0.451	0.568	0.550	0.542	0.636
Weighted average nozzle port velocity in y-direction (Horizontal) (m/sec)	0.042	0.042	0.017	0.009	0.022	0.015
Weighted average nozzle port velocity in z-direction (Downward) (m/sec)	0.315	0.315	0.343	0.404	0.327	0.497
Vertical jet angle (degree)	-35.0	-35.0	-31.2	-36.4	-31.1	-38.0
Horizontal jet angle (degree)	0	0	0	0	0	0
Average jet speed(m/sec)	0.55	0.55	0.66	0.68	0.63	0.81
Flow rate (kg/sec)	0.286	0.286	0.276	0.296	0.145	0.427
Averaged jet force (N)	0.157	0.157	0.182	0.201	0.091	0.346
Maximum velocity magnitude (m/sec)	0.98	0.98	1.10	1.17	0.87	1.28
Weighted average turbulent kinetic energy(m ² /s ²)	0.022	0.022	0.043	0.020	0.033	0.019
Weighted average turbulent kinetic energy dissipation rate (m ² /s ³)	0.782	0.783	2.12	0.797	1.47	0.731
Back-flow zone (%)	17.2	17.2	0	16.9	0	17.2

Jet Velocity Profiles

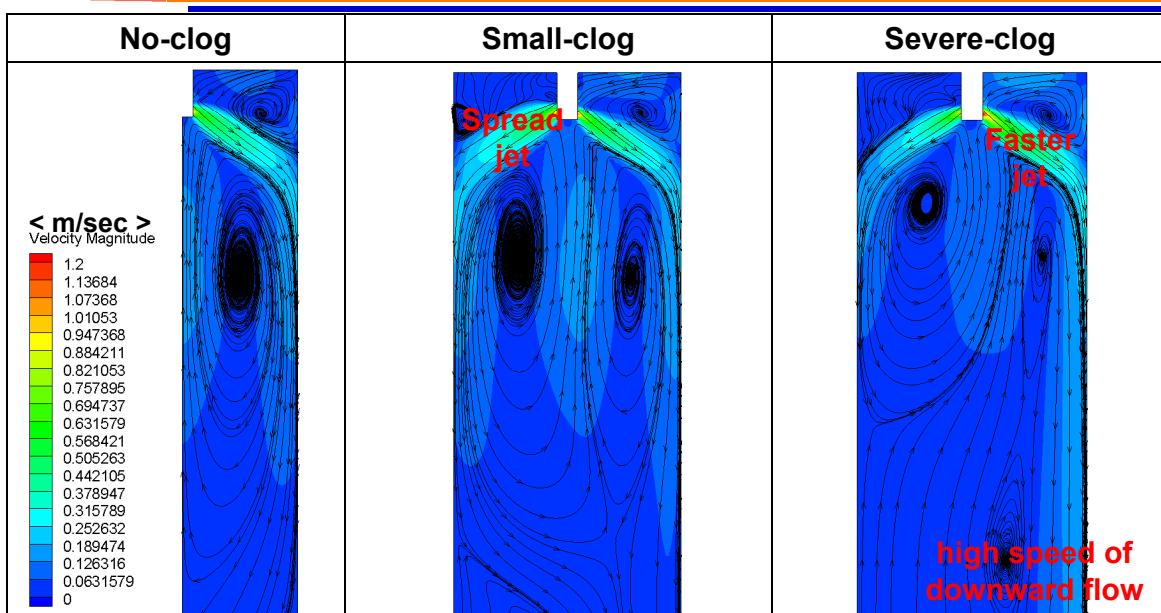


Jet force (Flow rate): N (kg/sec)

	Left	Right	Total
No-clog	0.157 (0.286)	0.157 (0.286)	0.314 (0.572)
Small-clog	0.182 (0.276)	0.201 (0.296)	0.383 (0.572)
Severe-clog	0.091 (0.145)	0.346 (0.427)	0.437 (0.572)

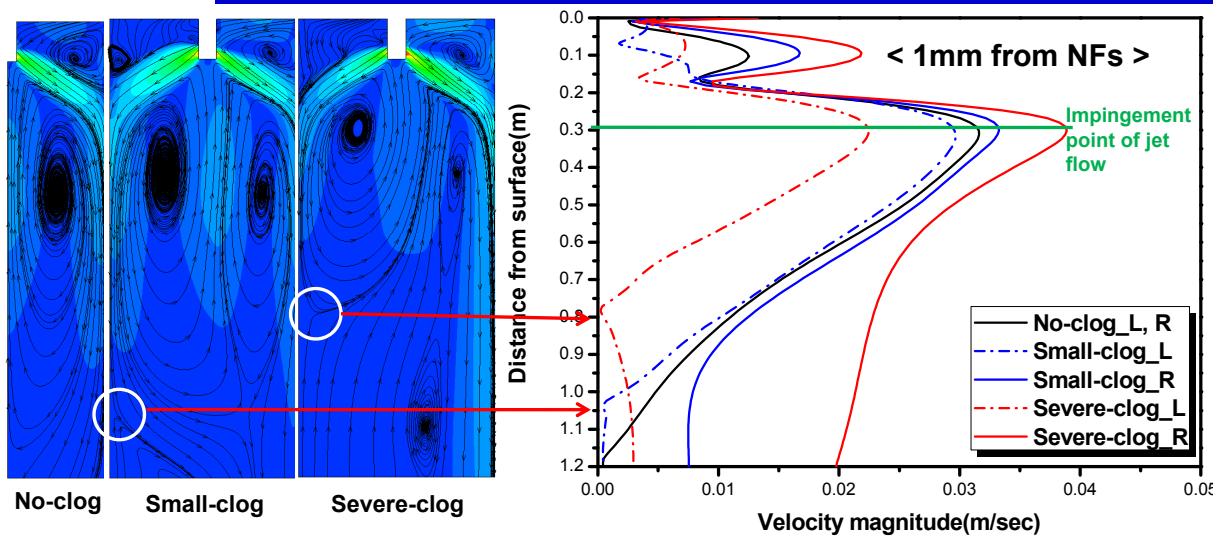
- Flow rate at clogged port decreases, but flow rate at non-clogged port increases
- Faster jet at non-clogged port than clogged port because of increasing flow rate
- Increased flow rate and velocity magnitude induce higher jet force

Asymmetric Flow in the Mold with Nozzle Clogging



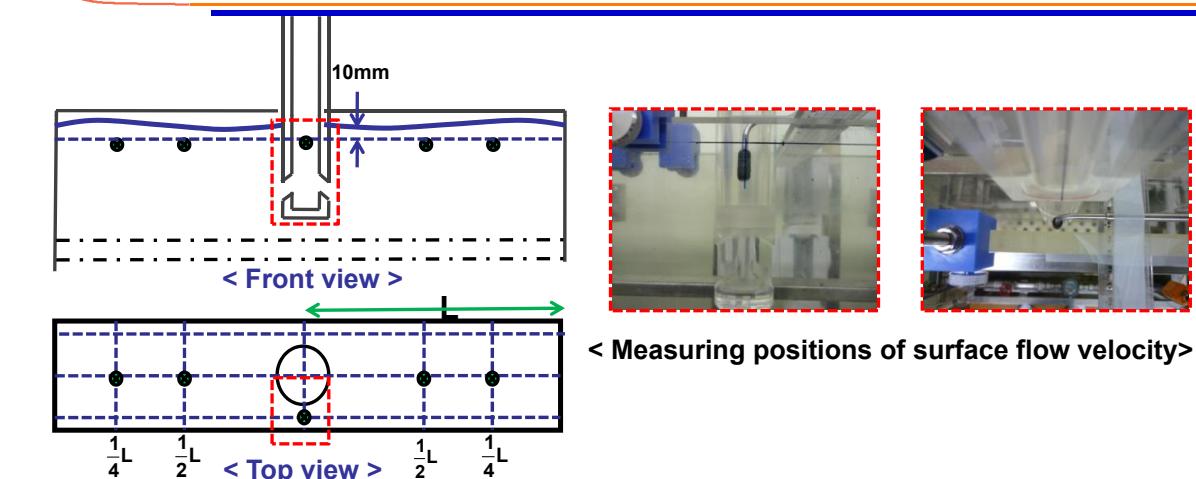
- Nozzle clogging causes asymmetric flow in a mold (Unbalanced double roll pattern)
- With clogged nozzle, surface flow from right side cross the surface and suppress the uprising flow from left NF
- In severe-clog case, it is possible for inclusions to penetrate deeply down into a mold

Velocity near Narrow Faces



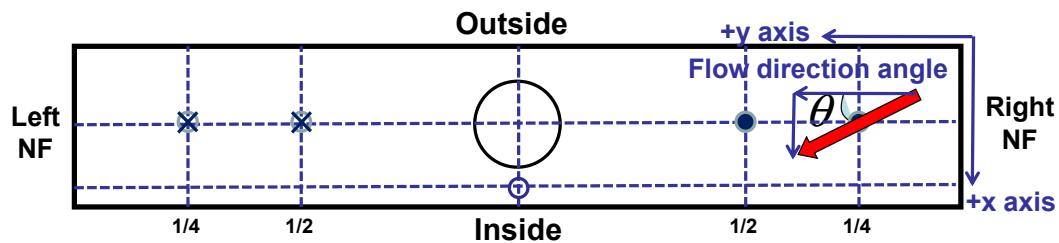
- Jet impingement point on NFs is ~0.3m below free surface
- Mold flow near NFs is faster on the same side as non-clogged port
- More clogging causes more asymmetry between left and right side
- There exists stagnant flow region in the mold with clogged nozzle

Measuring Surface Velocity



- Measure velocity profiles near surface with current meter sensors during 1000sec
- Compare velocity profiles on $\frac{1}{4}$, $\frac{1}{2}$ points from NFs, gap between SEN and mold inner wall
- Calculate average velocity magnitude, flow direction angle

Quantifying Averaged Surface Velocity Vector

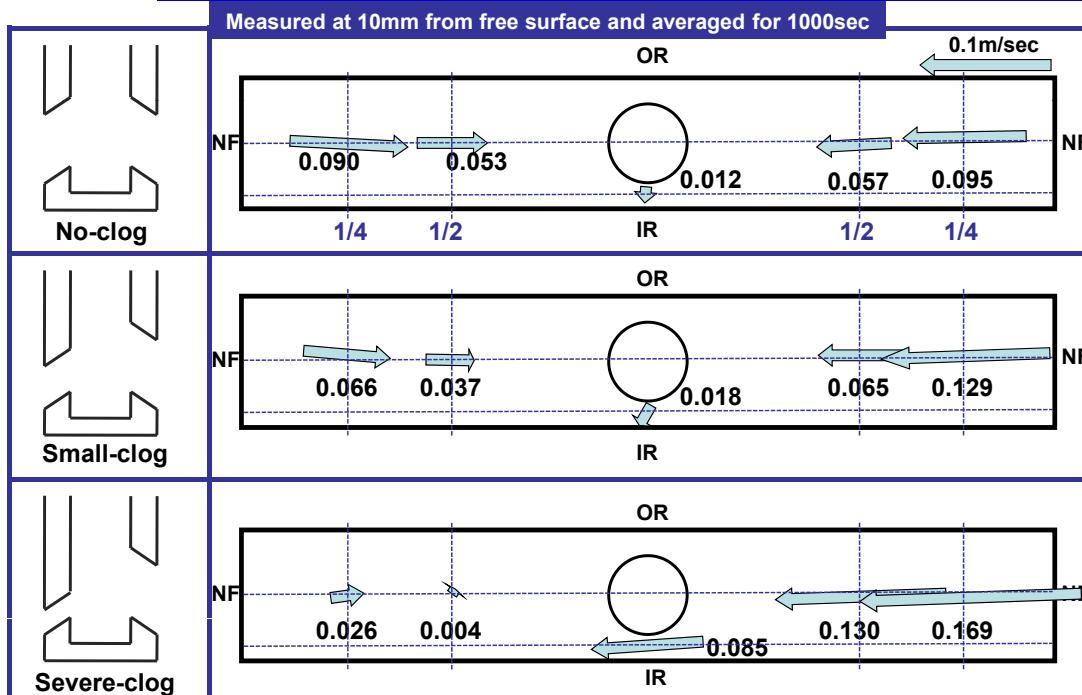


Determining the **flow direction angle** from averaged velocity components

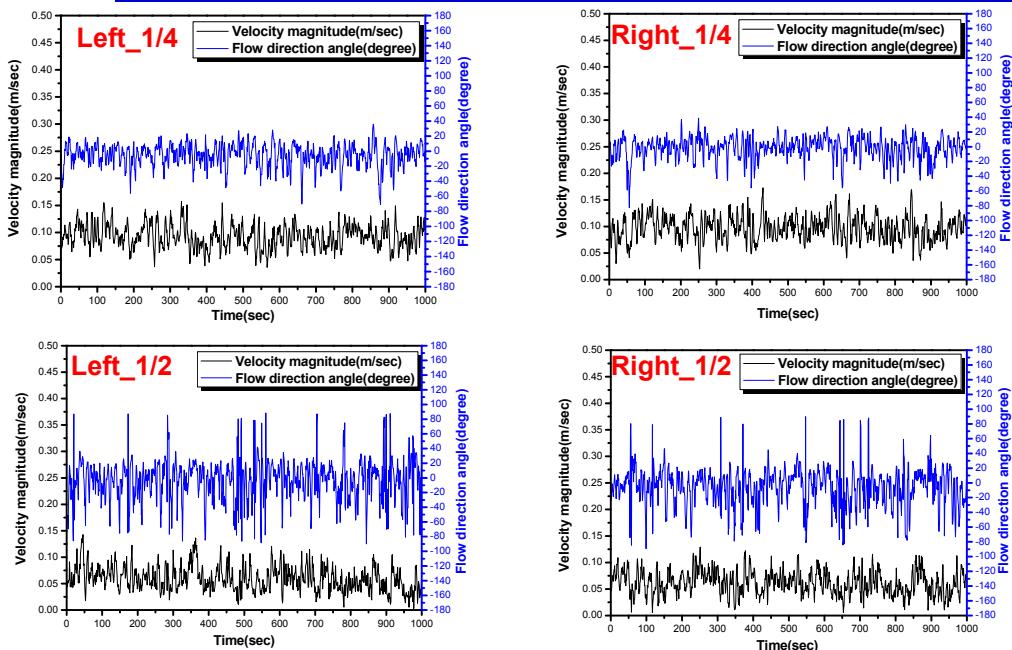


**Quantifying vector-averaged surface flow
with flow direction angle and velocity magnitude**

Averaged Surface Flow Pattern (Experimental Results)

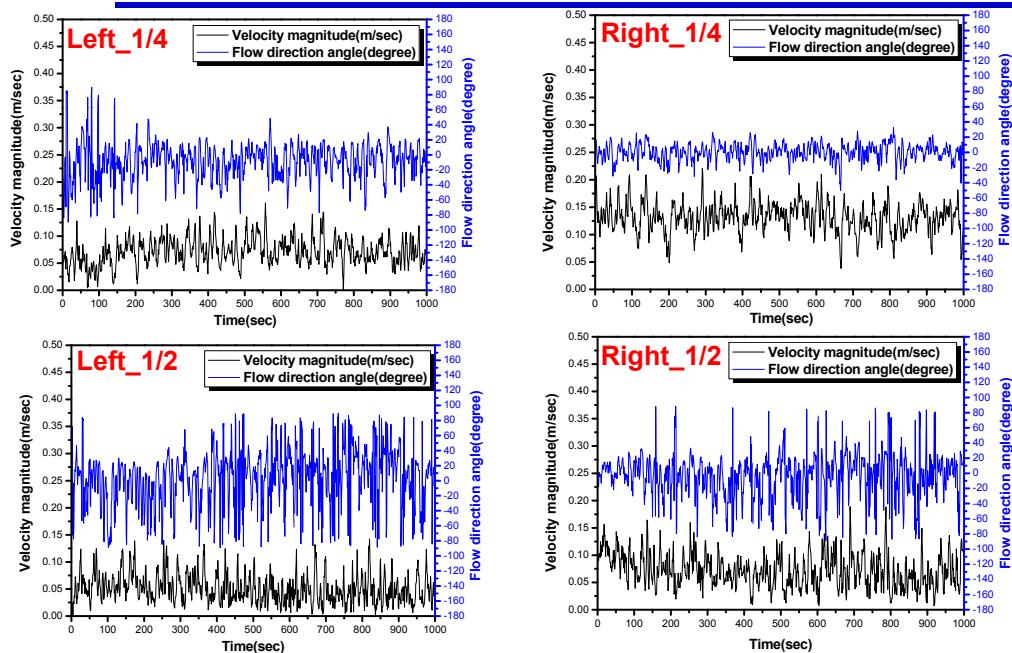


Speed & Direction Variation with No-Clog Nozzle



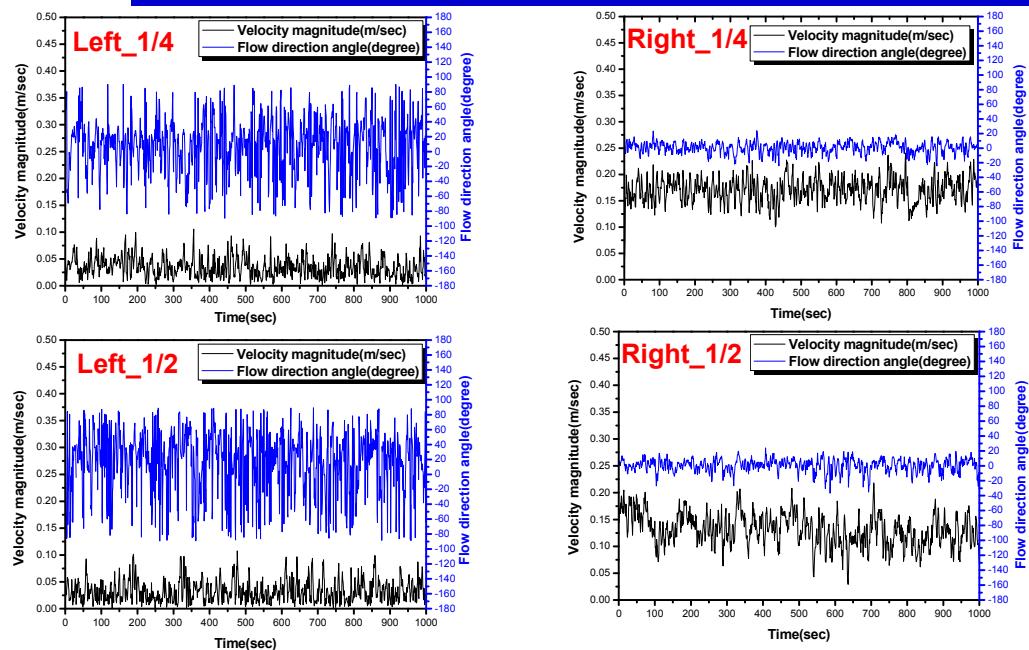
- Surface flow becomes slower and more chaotic toward SEN

Speed & Direction Variation with Small-Clog Nozzle



- Surface flow from right NF is faster and more consistent than left NF
 - Surface flow at the left (slower) side is more chaotic than right side

Speed & Direction Variation with Severe-Clog Nozzle



- There is same trend as more clogged nozzle , but more severe
- Flow direction is more consistent on faster right side

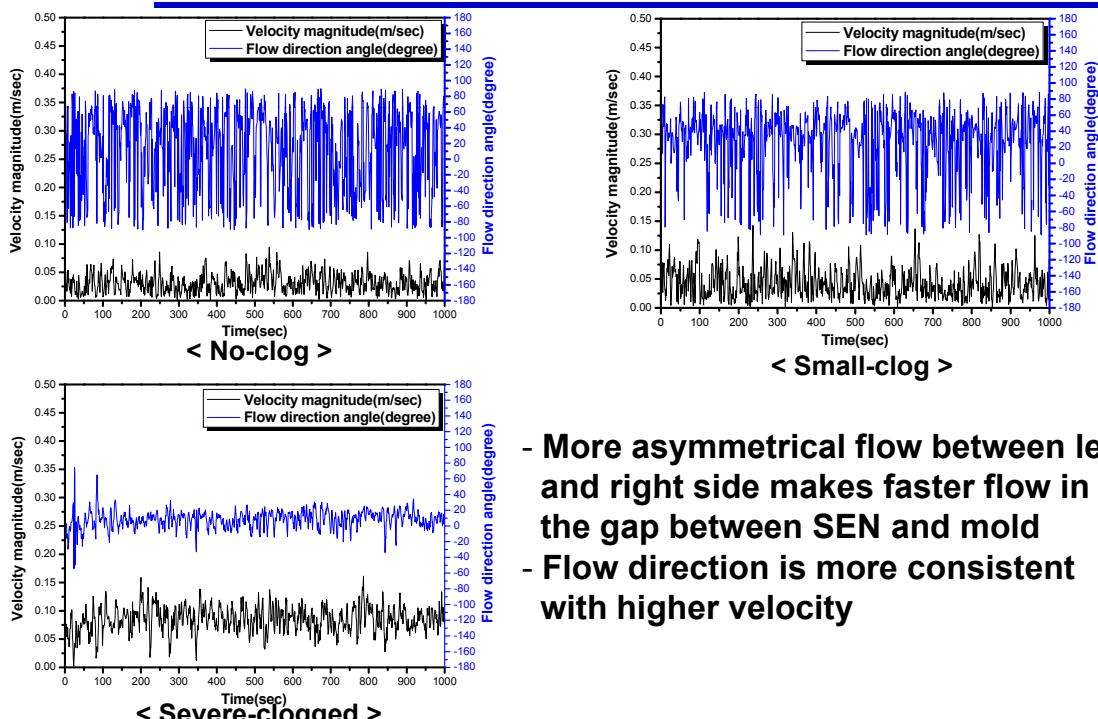
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Speed & Direction Variation in the Gap between SEN and Mold



- More asymmetrical flow between left and right side makes faster flow in the gap between SEN and mold
- Flow direction is more consistent with higher velocity

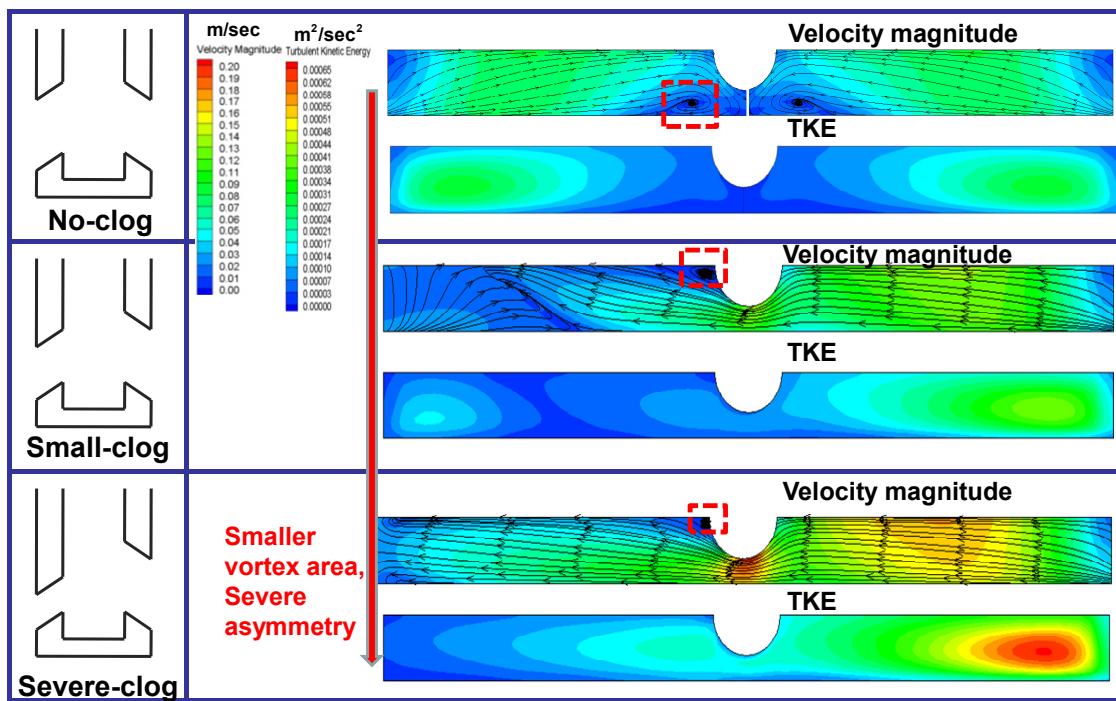
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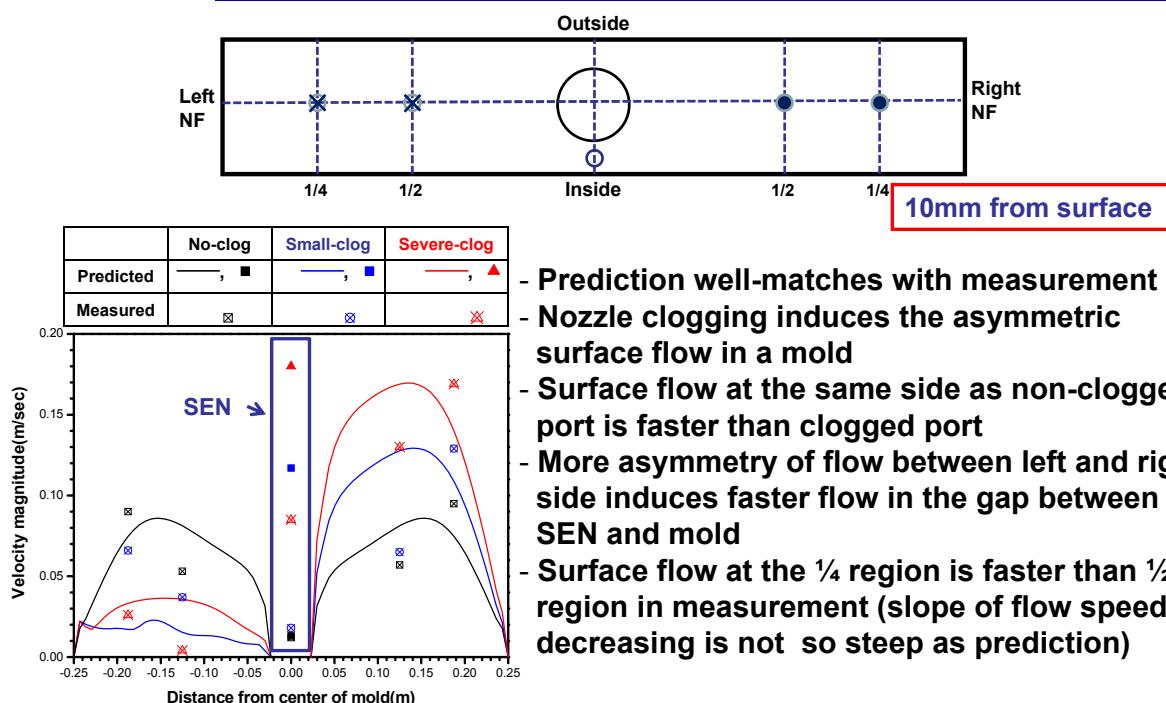
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Velocity Magnitude and Turbulent Kinetic Energy (TKE)



Surface Velocity Results (Prediction and Measurement)





Comparison of Predicted Averaged Surface Velocity with Measured One

Velocity magnitude (m/sec)

		Left		Gap between SEN and mold inner wall	Right	
		1/4	1/2		1/2	1/4
No-clog	Predicted	0.078	0.080	0.013	0.080	0.078
	Measured	0.090	0.053	0.012	0.057	0.095
Small-clog	Predicted	0.018	0.015	0.117	0.126	0.111
	Measured	0.066	0.037	0.018	0.065	0.129
Severe-clog	Predicted	0.032	0.033	0.180	0.167	0.142
	Measured	0.026	0.004	0.085	0.130	0.169

- Model over-predicts experiments in the gap between SEN and mold inner wall; Standard $k-\epsilon$ model can't accommodate flow speed with direction variation (Real turbulent flow decreases the averaged surface flow)
- In severe-clog case, model predicts that surface flow from right side crosses the surface and suppresses the uprising flow from left NF
- Computational model predicts the region of the fastest surface flows at $\frac{1}{2} L$ region



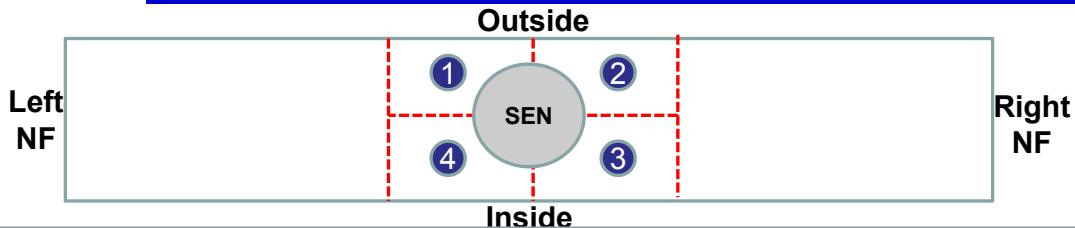
Comparison of Predicted Turbulent Kinetic Energy (TKE) with Measured One

Turbulent kinetic energy ($10^{-4} \text{m}^2/\text{sec}^2$)

		Left		Gap between SEN and mold inner wall	Right	
		1/4	1/2		1/2	1/4
No-clog	Predicted	2.30	1.77	0.414	1.77	2.30
	Measured	5.05	6.18	5.42	5.29	5.46
Small-clog	Predicted	0.620	0.920	3.79	3.40	5.65
	Measured	6.38	9.59	10.8	9.63	6.53
Severe-clog	Predicted	1.48	2.00	7.64	6.56	10.9
	Measured	4.42	7.32	8.20	6.21	5.19

- Measured TKE is greater than predicted one; anisotropy of real turbulence; directional variation of surface flow affects TKE together with speed variation
- Vortexing flow pattern causes higher turbulent kinetic energy at left region near SEN in measurement

Counting Vortex Formation



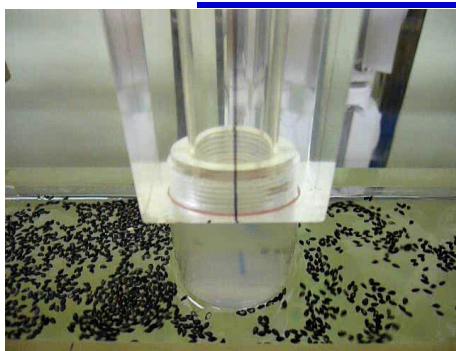
-Visualization of vortex formation:

- ✓ Scatter sesame seeds (tracer particles) at surface of water-model mold
- ✓ Record videos and take pictures
- Counting vortex formation
 - ✓ Divide the four region near SEN
 - ✓ Count the number of each region in a time interval
(Criterion of vortex: over 2 rotations)

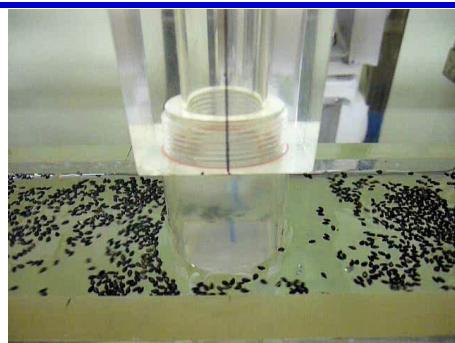
Left region VS Right region: $1 + 4$ VS $2 + 3$

Outside region VS Inside region : $1 + 2$ VS $3 + 4$

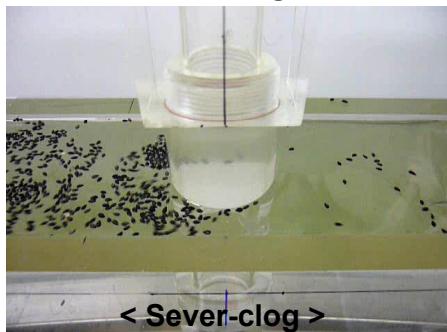
Vortex Formation with Clogged Nozzle



< No-clog >



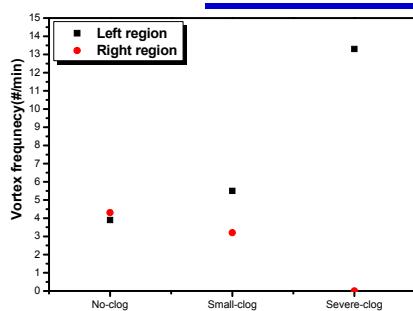
< Small-clog >



< Sever-clog >

- Most vortices are formed at 4 regions near SEN in the cases of no and small-clog cases.
- All vortices are formed at left region near SEN with severe-clog case
- Nozzle clogging causes asymmetric vortex formation
- More vortices form at the left region of SEN with the nozzles with clogged left port

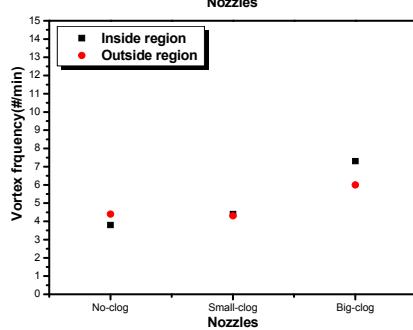
Vortex Formation Frequency



Vortex frequency(#/min)

	Left	Right	Total
No-clog	3.9 (48%)	4.3 (52%)	8.2
Small-clog	5.5 (63%)	3.2 (37%)	8.7
Severe-clog	13.3 (100%)	0	13.3

< Left region VS Right region >



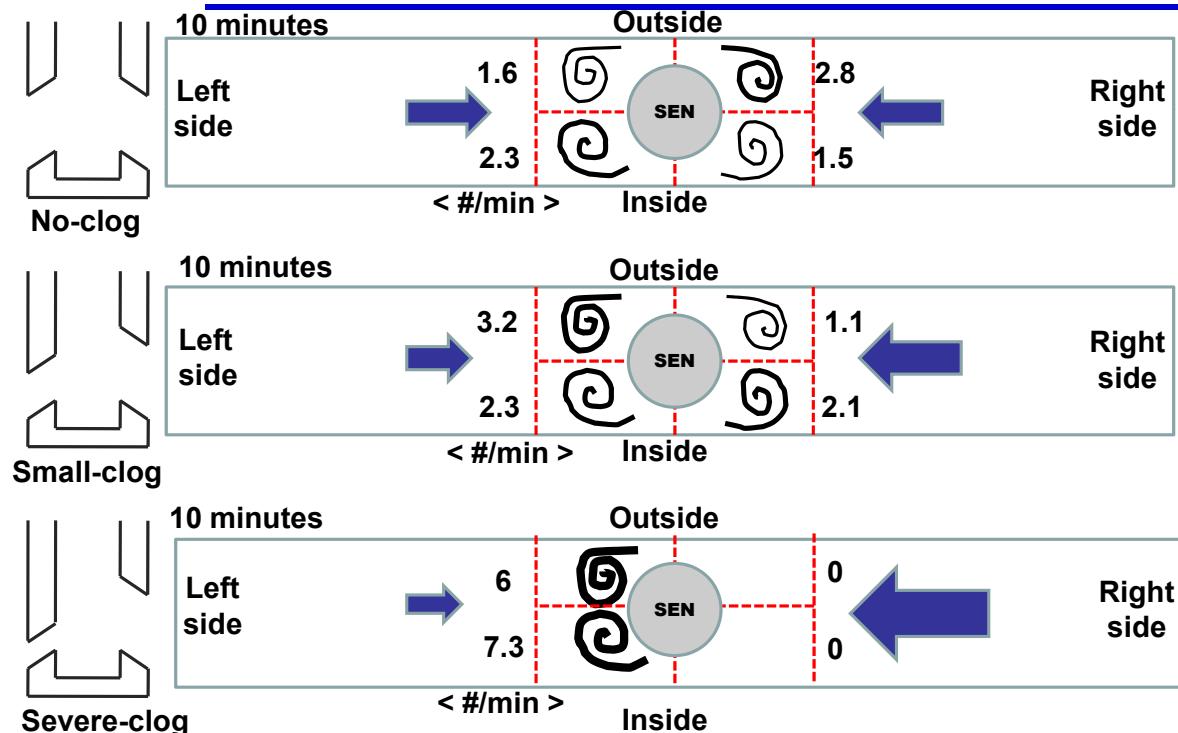
Vortex frequency(#/min)

	No-clog	Small-clog	Severe-clog
Outside	4.4 (54%)	4.3 (49%)	6 (45%)
Inside	3.8 (46%)	4.4 (51%)	7.3 (55%)
Total	8.2	8.7	13.3

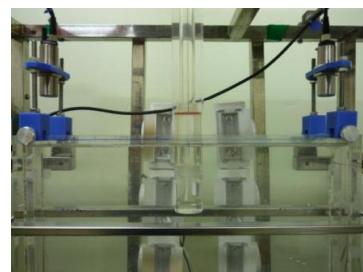
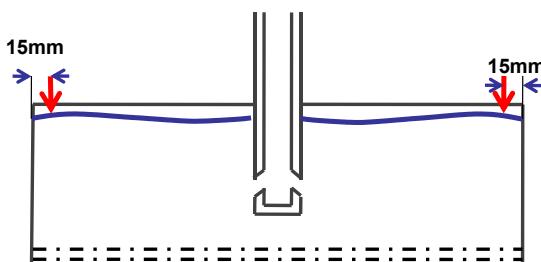
< Inside region VS Outside region >

- Vortices are caused by asymmetric flow between right and left region
- Vortex frequency increases with clogging due to greater diff. of right/left velocity

Vortex Formation Frequency (Visualization)



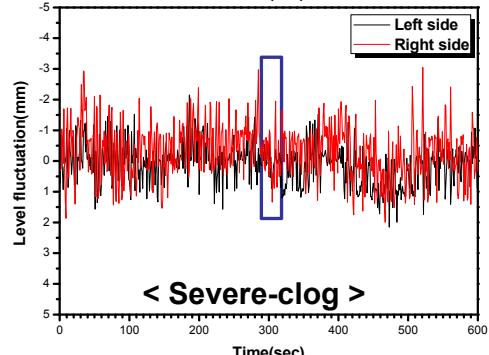
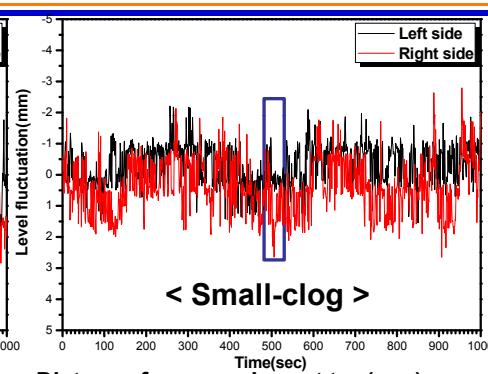
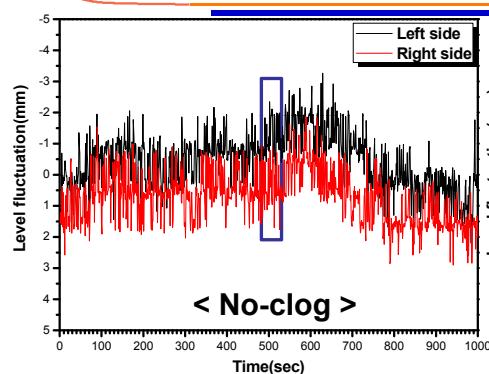
Measuring Level Fluctuation



< Measuring positions of level fluctuation >

- Measure level fluctuation on the surface near NFs with ultrasonic displacement sensors
- Compare fluctuation profiles at 15mm position from both NFs
- Calculate average level and standard deviation of level
- Transfer level fluctuation profiles to power spectrum by FFT (Fast Fourier Transform) analysis

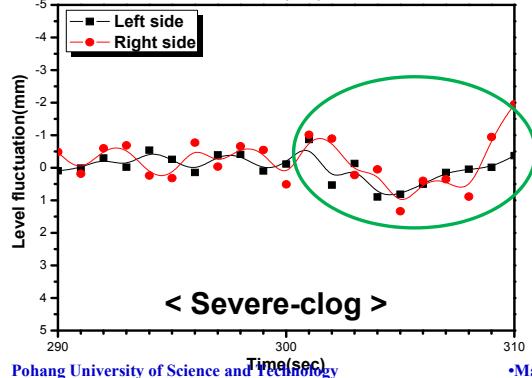
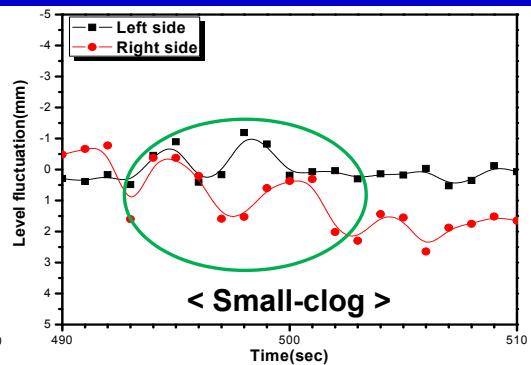
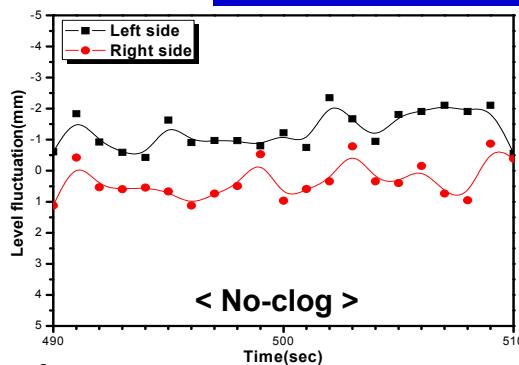
Histories of Level Fluctuation



	Left	Right	
No-clog	Avg	61	60
	Stddev	0.9	0.8
Small-clog	Avg	62	61
	Stddev	0.7	0.9
Severe-clog	Avg	62	62.5
	Stddev	0.7	0.9

Slightly
higher
averaged
level with
nozzle
clogging

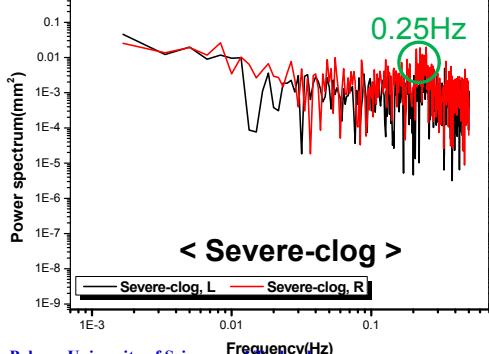
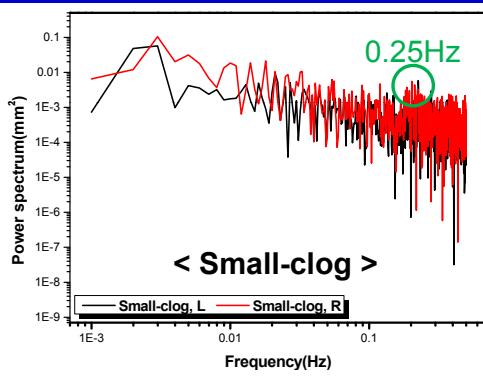
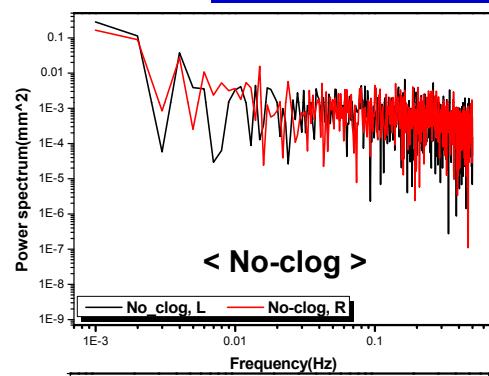
Characteristics of Level Fluctuation



- Smooth level fluctuation with non-clogged nozzle
- Abruptly severe level fluctuation with clogged nozzle (more severe with more clogged nozzle)

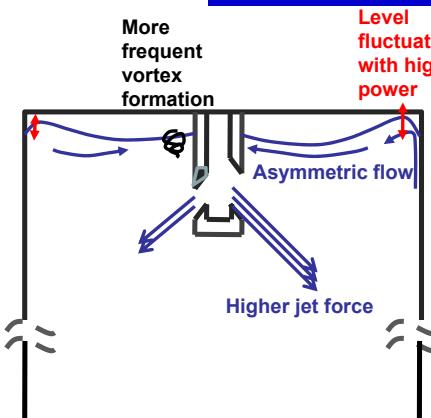
Severe level fluctuation disturbs uniform initial solidifying shell

Power Spectrum of Level Fluctuation



- Level fluctuation with non-clogged nozzle shows more turbulent trend
- With clogged nozzle, there is higher power at the right NF (non-clogged port side)
- Asymmetric flow by nozzle clogging creates periodic asymmetric fluctuation (high power at 0.25 Hz)

Summary



"Phenomena in the mold with clogged nozzle"

- Nozzle clogging effects has been studied with 3 cases nozzles (No, Small and Severe-clog)
- **Asymmetric flow**
 - ✓ Asymmetric jet from clogged nozzle cause asymmetric flow in a mold
 - ✓ The surface flow at the side with non-clogged port is faster than clogged port
 - ✓ More asymmetry of flow between left and right side induces faster flow at the gap between SEN and mold
- **Vortex formation**
 - ✓ Vortices are caused by the asymmetric flow between right and left side
 - ✓ More vortices form at the left region of SEN with the nozzle having clogged left port
- **Level fluctuation**
 - ✓ The surface level at the same side as non-clogged port is higher with higher power
- **Comparison of results between experimental and computational works**
 - ✓ Standard $k - \epsilon$ model shows the well matched trend with measurement
 - ✓ Real vortexing flow pattern makes the difference of turbulent kinetic energy between measurement and prediction (need of studying transient modeling)

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