ANNUAL REPORT 2011

UIUC, August 18, 2011

Transient Flow, Vortex Formation, and Slag Entrainment in the Mold with Water Models and URANS Modeling

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Research Scope

Background:

- Transient flow induces asymmetric flow by time, and this phenomena could be severe with nozzle clogging.
- Asymmetric flow could induce abnormal fast surface flow and vortex formation, resulting in slag entrainment.
- It is important to understand transient fluid flow in the mold for investigating the effect of asymmetric surface flow on vortex formation and slag entrainment.

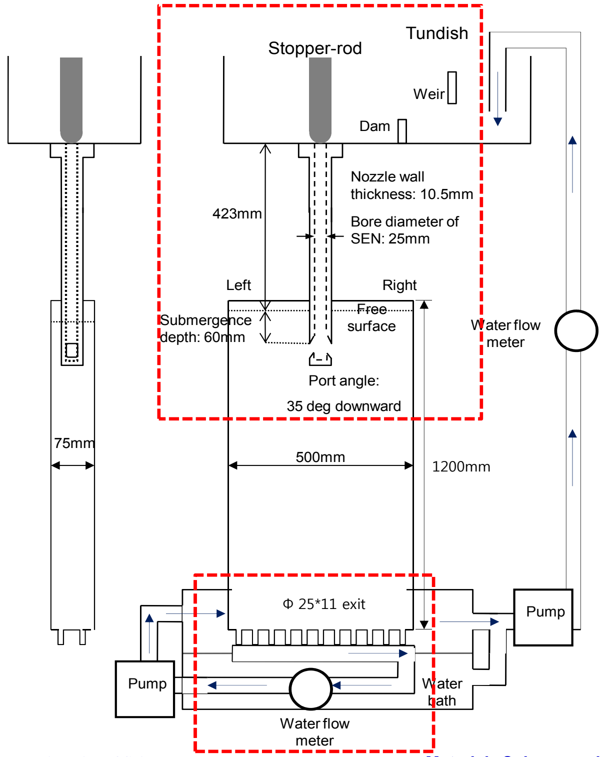
Objective:

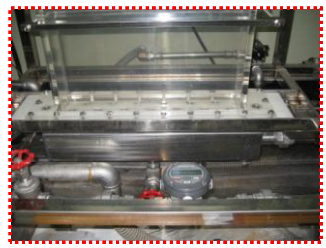
- Study effect of transient flow and nozzle clogging on asymmetric surface flow.
- Investigate effect of transient asymmetric surface flow on vortex formation and slag entrainment.
- Examine capability of Filtered URANS model for modeling time-dependent surface flow and vortex formation in water model.

Methodology:

- Water model experiment to quantify transient surface flow, vortex formation and slag entrainment.
- Computational modeling to explain flow pattern with Steady RANS and Filtered URANS model.

Schematic of 1/3 Scale Water Model





3 Nozzles to Study Clogging Effects

No-clog	Small-clog	Severe-clog
		

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
Ratio of area between left and right		*1*	*0.67*	*0.33*
Ratio of area between two ports and nozzle bore		*2.54*	*2.11*	*1.69*
Port angle (degree)		-35	-35	-35

Left port			Right port
No-clog	**Small-clog**	**Severe-clog**	**All cases**
23.3mm × 26.7mm	19.0mm × 21.8mm	13.5mm	23.3mm × 26.7mm

Clog in left nozzle port
- Small-clog (33% clog)
- Severe-clog (67% clog)

Processing Conditions for 1/3 Scale Water Model

Similarity between the 1/3 scale water model and the real caster conditions

➡ Froude number (Ratio of Inertia force to gravitational force) = $v / \sqrt{gL}$

	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
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)
Nozzle(well bottom type) port angle	35 degree downwards	
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

Computational Model

- Reynolds-Averaged Navier-Stokes (RANS) model: Standard $k-\varepsilon$ (SKE) model
  ✓ SKE model well predicts time-averaged flow with reasonable accuracy and efficiency but, has deficiencies to predict turbulence quantities.

- Filtered Unsteady Reynolds-Averaged Navier-Stokes (FURANS) model:
  ✓ Johansen et al. improved on the SKE model by adopting the filtering concept*

$$\text{Turbulent viscosity } (\nu_t): C_\mu \frac{k^2}{\varepsilon} \rightarrow \boxed{C_\mu \min(1.0, f)\frac{k^2}{\varepsilon}\ \left(f = \frac{\Delta\varepsilon}{k^{3/2}}\right)}$$

  ✓ Chaudhary et al. reported that the Filtered URANS model performs between LES and Steady RANS model with capturing the long-time variations of mold flow pattern of continuous caster**
  ✓ The cube root of Maximum cell volume in domain is adopted for filter size using UDF

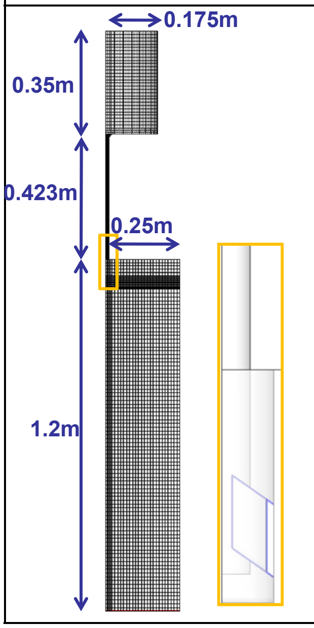
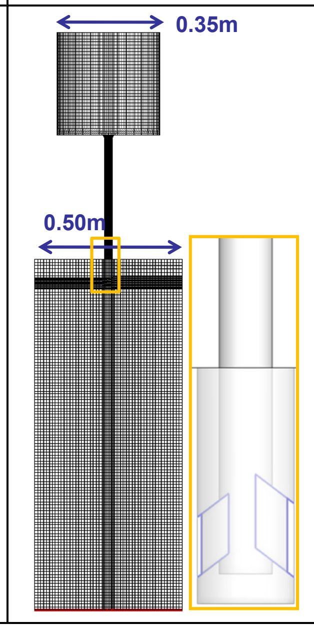
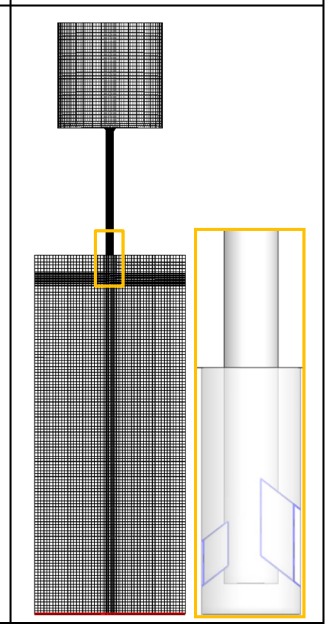
$$\boxed{\text{Filter size } (\Delta) = \sqrt[3]{\text{Maximum cell volume in the domain}}}$$

- Steady SKE and FURANS model are adopted for predicting time-averaged and -dependent flow in the mold of 1/3 scale water model

* Stein T. Johansen et al., Heat and Fluid Flow, Vol. 25 (2004), p. 10-21
** Rajneesh Chaudhary et al., Metallurgical and Materials Transaction B, In press

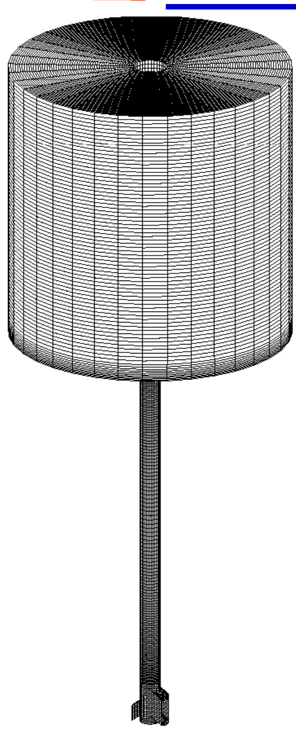
Mesh in Computational Domain for SKE Model

- Hexa-cells used in the computational domain
- No-clog: 0.107 million (quarter domain), Small-clog: 0.205 million (half domain), Severe-clog: 0.203 million (half domain)

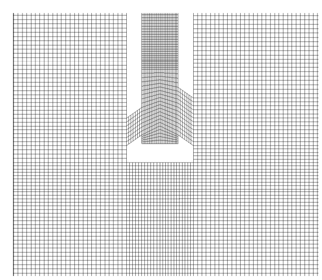
No-clog	Small-clog	Severe-clog
		

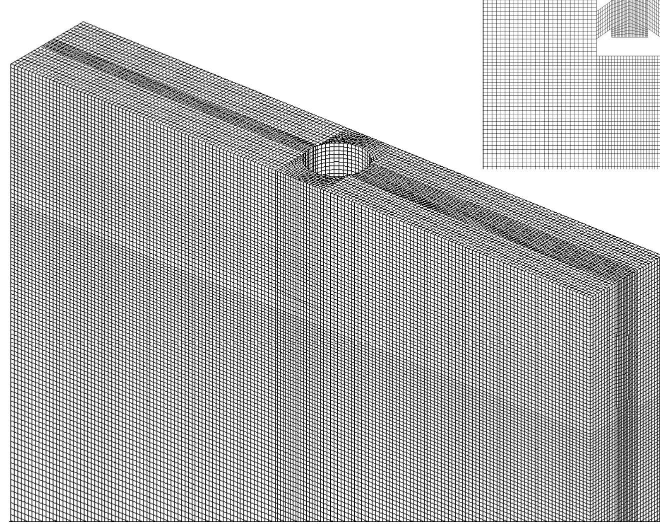
Mesh in Computational Domain for Filtered URANS Model

- Hexa-cells used in the computational domain
- Severe-clog case: ~1.4 million (full domain)



< Nozzle >





< Mold >

Boundary Conditions

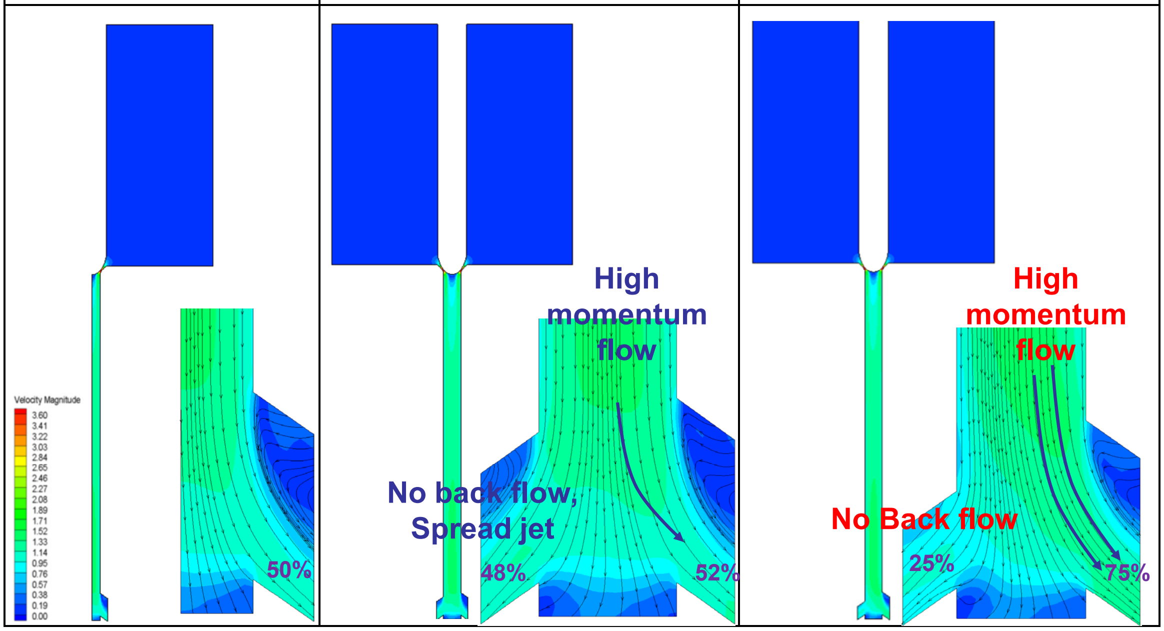
- **Steady RANS (SKE model):**
  - Wall boundary with no-slip condition using standard wall functions.
- **Filtered Unsteady RANS model:**
  - Wall boundary with no-slip condition using Enhanced Wall Treatment (EWT).
- **For both Steady RANS and Filtered URANS model**
  - Constant velocity magnitude (0.001195 m/sec) with $10^{-5}\ m^2/sec^2$ turbulent kinetic energy and $10^{-5}\ m^2/sec^3$ turbulent dissipation rate at the inlet
  - 0 shear stress conditions for free top surface.
  - Constant pressure (0 gauge pascal) with $10^{-5}\ m^2/sec^2$ turbulent kinetic energy and $10^{-5}\ m^2/sec^3$ turbulent dissipation rate at the mold bottom outlet

Numerical Methods

- **Steady RANS (SKE model):**
  - Calculating with combined nozzle and mold domain
  - Semi-Implicit Pressure Linked Equations (SIMPLE) method for pressure-velocity coupling.
  - 1st order upwind scheme to discretize convection terms.
  - Convergence in almost all cases until scaled residuals were reduced to stable 10^{-4}
- **Filtered Unsteady RANS model:**
  - Calculating with combined nozzle and mold domain.
  - Fractional Step for pressure-velocity coupling.
  - 1st order upwind scheme to discretize convection terms.
  - Residuals were reduced by 3 orders magnitude at every time-step
  - Data collecting for 12.5 sec after 24 sec for stabilizing flow with 0.005 sec time-step

Flow Pattern in the SEN (SKE model)

No-clog	Small-clog	Severe-clog



- Nozzle port clogging causes asymmetric flow in a nozzle

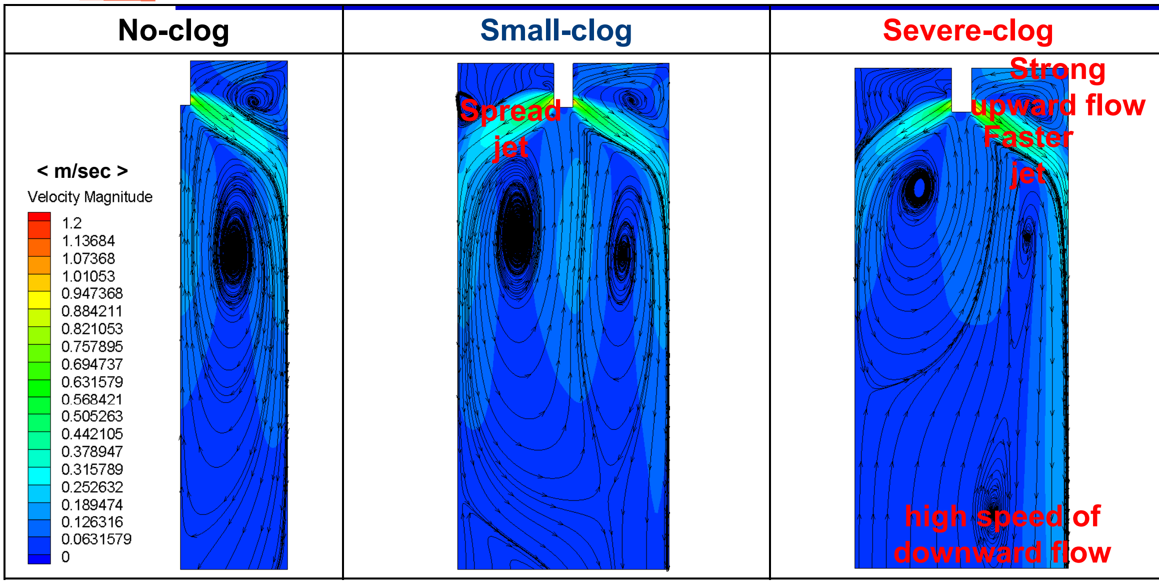
Jet Characteristics (SKE model)

	No-clog		Small-clog		Severe-clog	
	Left	Right	Left	Right	Left	Right
Vertical jet angle (degree)	-35.0	-35.0	-31.2	-36.4	-31.1	-38.0
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

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

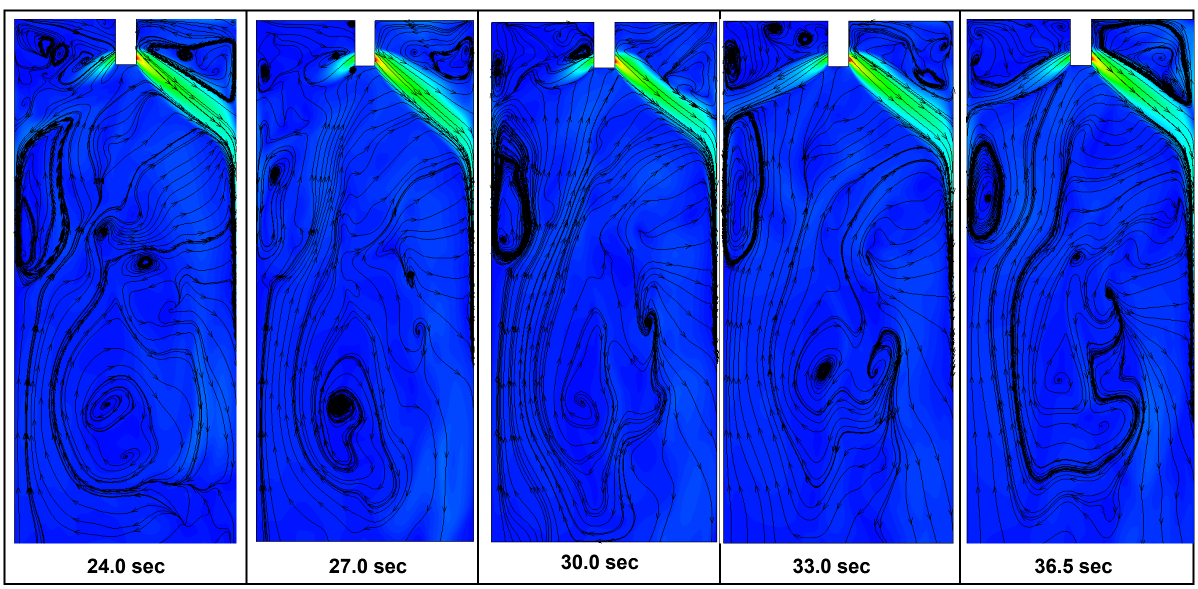
- Increasing asymmetry of the port sizes causes increased asymmetry of jet characteristics
- The vertical jet angle becomes larger (directed more steeply downwards) at the non-clogged port and smaller at the clogged port, relative to the average vertical jet angle with no clogging.
- Total jet force from both ports increases with nozzle clogging.

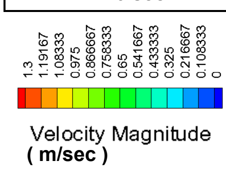
Flow Pattern in the Mold (SKE model)



- 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 and the strong upward flow can be detrimental in shearing off liquid slag from the top surface

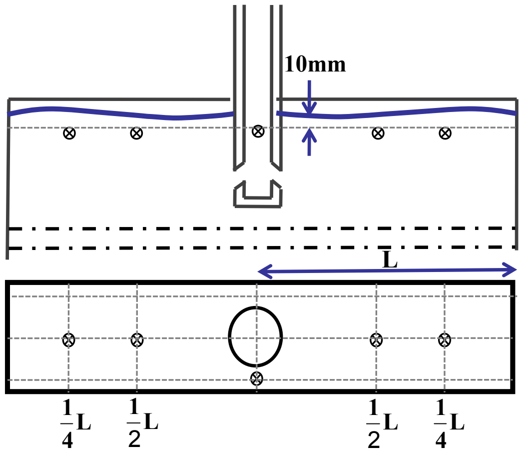
Transient Mold Flow Pattern with Severe-clog Nozzle (Filtered URANS model results)



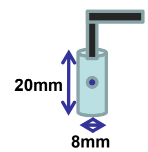


-Transient mold flow by time induces complex roll pattern at upper and lower regions.
- Asymmetry of upper roll pattern induces transient asymmetric surface flow by time.

Measuring Surface Velocity



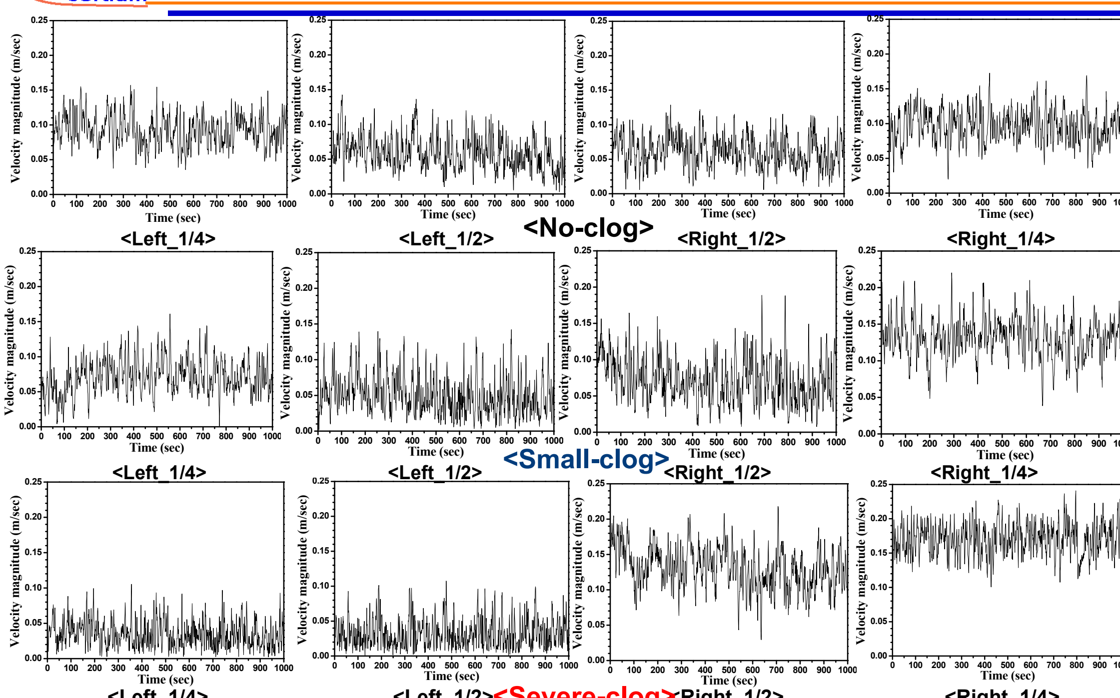
<Locations of electromagnetic current sensor>

	Electromagnetic current sensor
Response time	1Hz
Collecting data frequency	1Hz
Collecting data time	1000sec
Sensor head dimension	 20mm 8mm
Measuring direction	X,Y vector components

<Specifications of sensor>

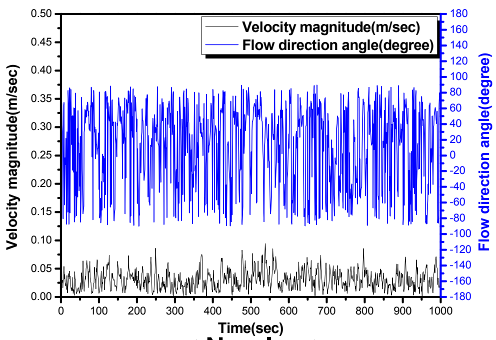
- Measure velocity profiles near surface with current meter sensor during 1000 sec
- Compare velocity profiles on ¼, ½ points from NFs, gap between SEN and mold inner wall
- Calculate velocity magnitude and flow direction angle by time

Instantaneous Velocity Histories at the Four Different Surface Positions

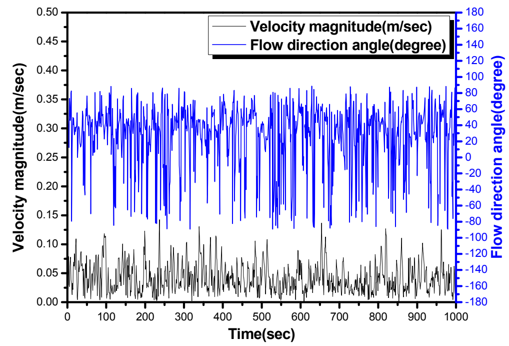


- Faster surface flow on non-clogged side
- More asymmetry of surface flow with more clogging

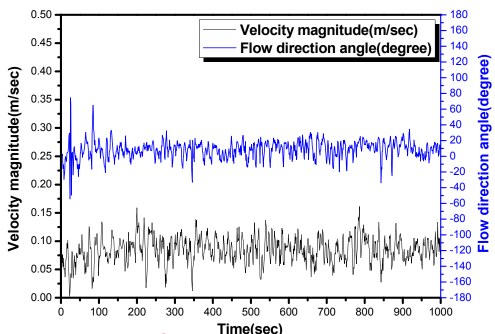
Speed & Direction Variation in the Gap between SEN and Inside



< No-clog >



< Small-clog >

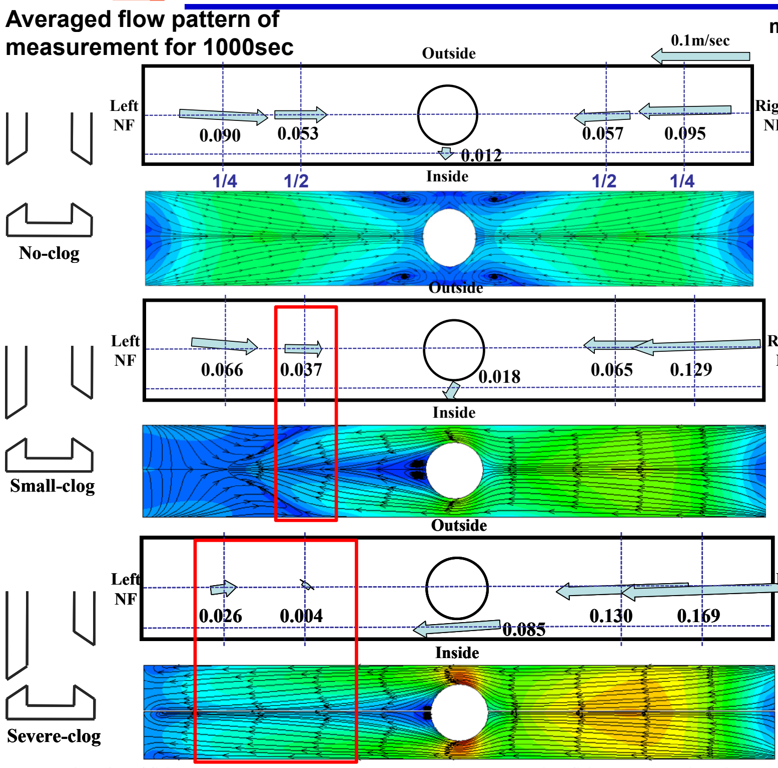


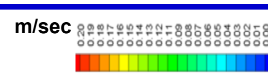
< Severe-clog >

- 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

Time-Averaged Surface Flow Pattern (SKE model)

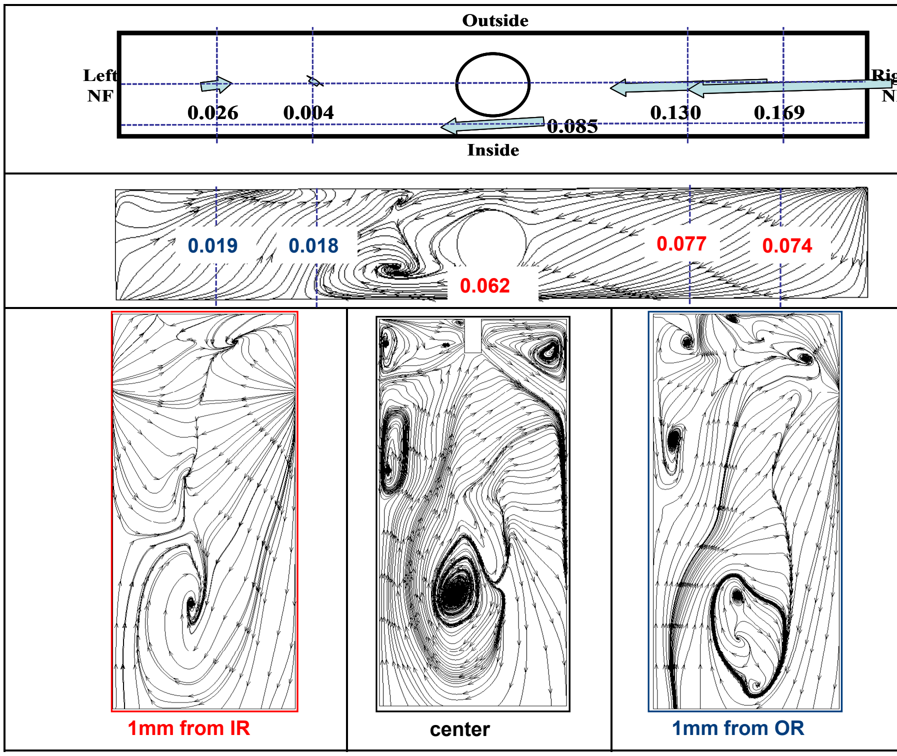
Averaged flow pattern of measurement for 1000sec





- Nozzle clogging causes asymmetry of the averaged surface flow.
- With no clogging, flow in the gap is directed toward the wide face, as the surface flows impinge from both sides.
- With a clogged left port, the stronger surface flow from the right side overcomes flow from the left side.
- The SKE model over-predicts the asymmetric suppression of surface flow by the faster flow

Comparison of Mold Flow Pattern between Measured and Predicted one by Filtered URANS Model

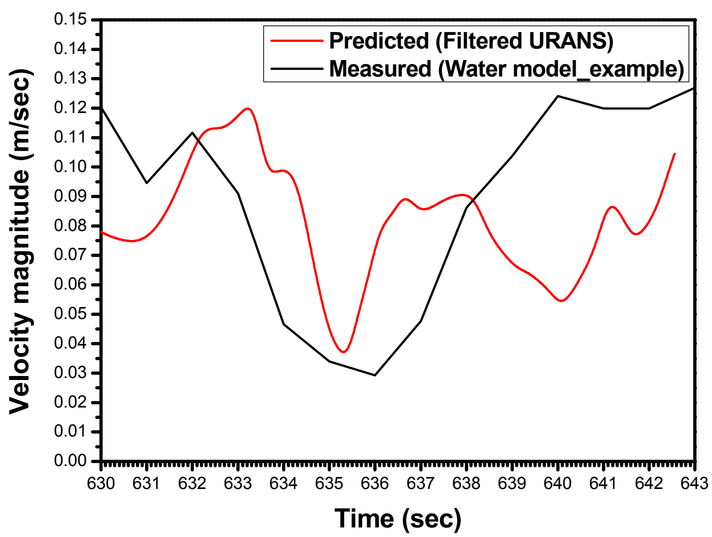


Averaged flow for 1000 sec of measurement.

Averaged flow for 12.5 sec of predictions

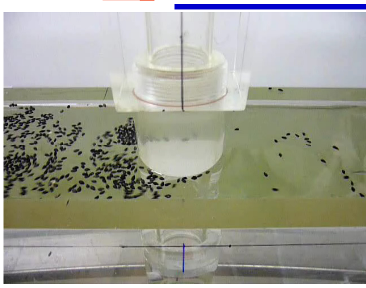
- URANS model predicts surface flow pattern well matched with measured one
- Asymmetric roll pattern of mold flow makes asymmetry of surface flow, resulting in vortex formation
- URNAS model should take more time for better matching with the time-averaged flow pattern of measurement

Comparison of Velocity Histories between Measured and Predicted one (Filtered URANS model)

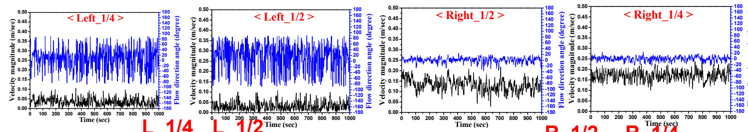


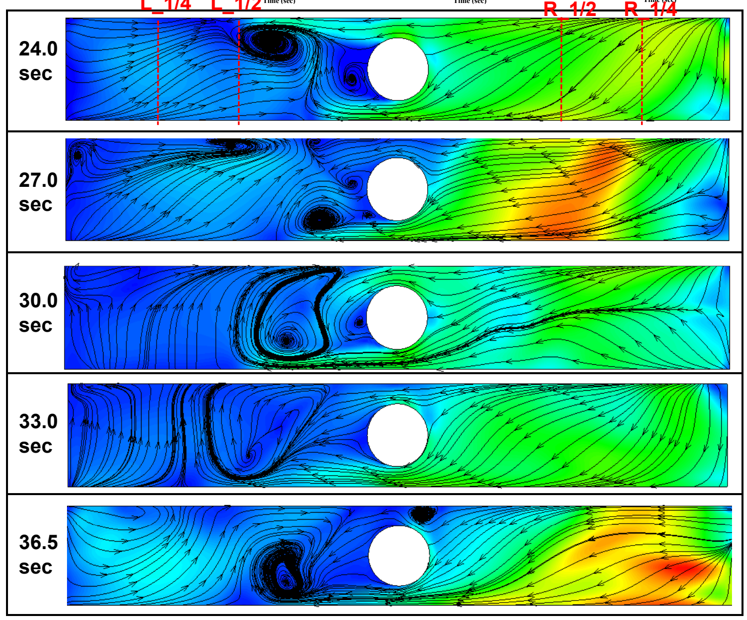
- Filtered URANS model well predicts velocity fluctuation during time.
- For much better predicting averaged velocity, It need much time than 12.5sec for Filtered URANS model

Transient Surface Flow Pattern and Vortex Formation (Filtered URANS model results)

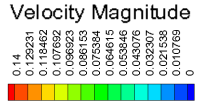


< Measured Vortex Formation >

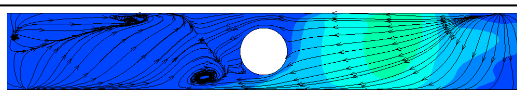
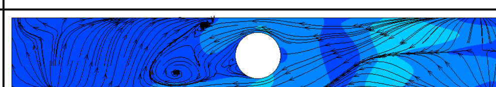
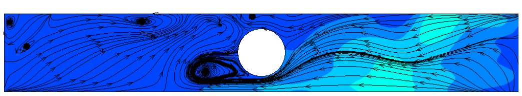
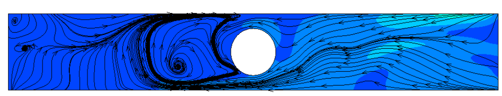
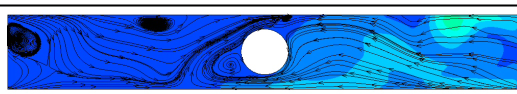
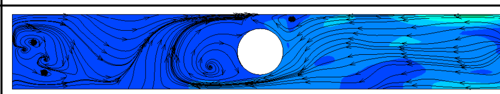
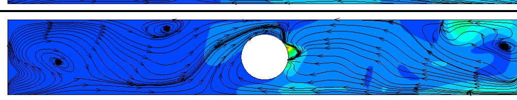
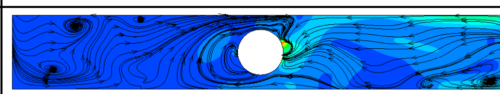


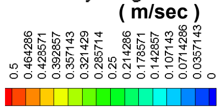


- Vortices form at the left side region of SEN with severe-clog
- Transient surface flow changes number, location and size of vortices
- In severe-clog case, flow direction angle histories at left regions confirm calculation accuracy of URANS model for predicting time-dependent flow



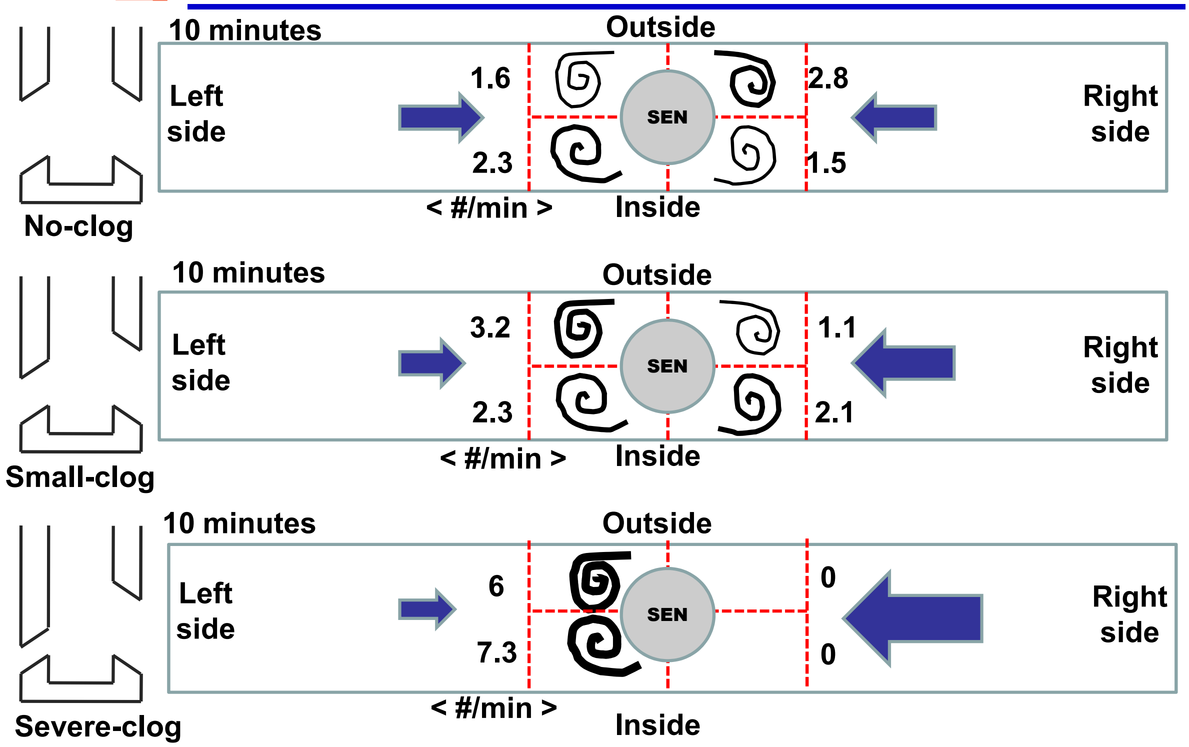
Vortex Strength with Transient Surface Flow (Filtered URANS model results)

	27 sec	30 sec
surface		
20mm below surface		
40mm		
60 mm		



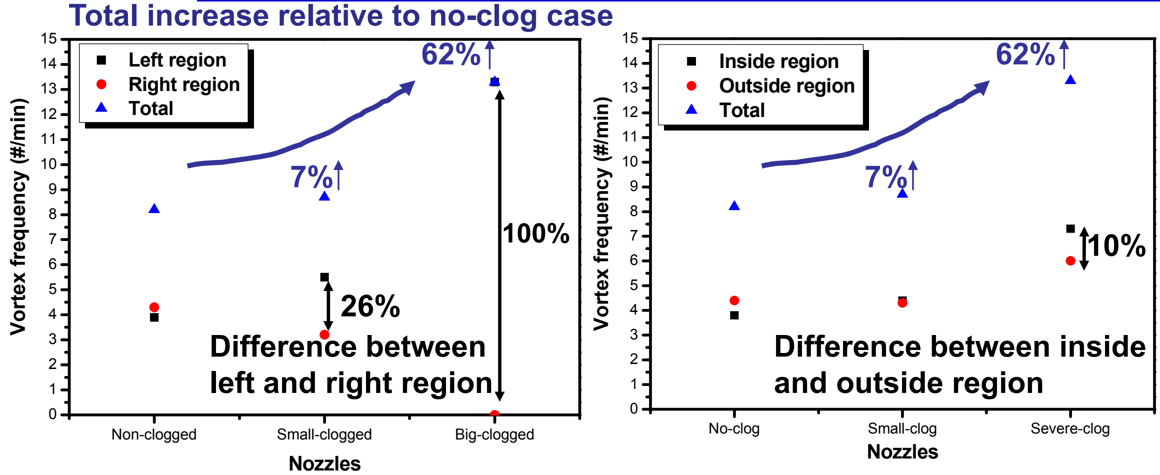
- Some vortices form at the surface and penetrate deep near nozzle port.
- Vortex could form at the region below the surface and expand along depth from free surface.

Measured Vortex Formation Frequency



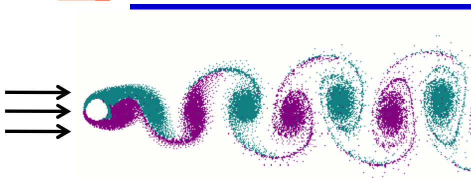
Asymmetry of Vortex Formation Frequency

Total increase relative to no-clog case



- Vortices are caused by asymmetric flow between right and left region
- Vortex frequency increases with clogging due to greater diff. of right/left velocity
- Asymmetry of vortex formation frequency between inside and outside region is not significant
- Transient turbulence flow makes vortices even though surface flow from both side is symmetric

Application of Karman Vortex Equation to Measured Surface Velocity in a 1/3 Water Model



< Karman Vortex >

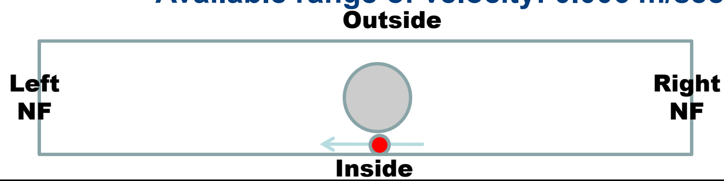
$$\frac{fd}{V} = 0.198\left(1 - \frac{19.7}{\mathrm{Re}}\right)$$

$$\mathrm{Re} = \frac{Vd}{\nu}$$

Theory: the formula will hold true for the range ($250<\mathrm{Re}<2*10^5$)

→ Available range of velocity: 0.006 m/sec< V <4.67 m/sec

< Water model>



	Theory	Application
f	Vortex frequency: #/sec	
d	Diameter of the cylinder	Diameter of the SEN: 0.046m
V	Velocity of the flow toward the cylinder	Averaged velocity: 0.085 m/sec
ν	Kinematic viscosity of the fluid	Kinematic viscosity of water: $1.004\times10^{-6} m^2/s$

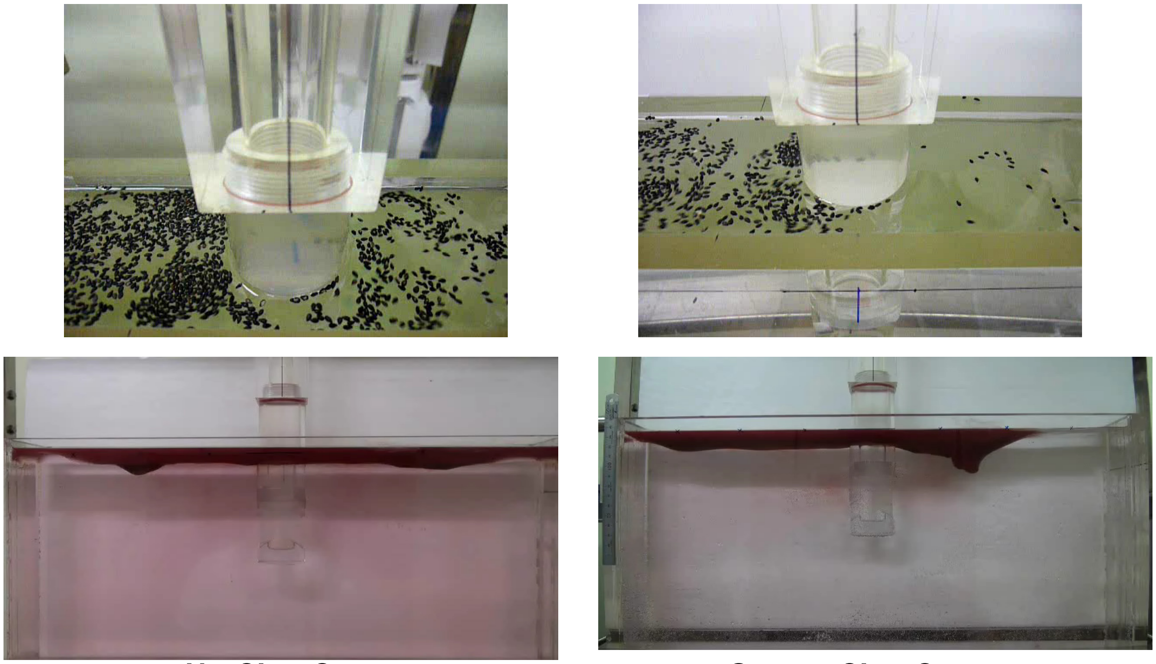
Relation between Transient Surface Flow and Vortex Formation Frequency

< Severe-clog nozzle case >

Predicted vortex formation frequency (With Karman vortex shedding equation)	0.39 Hz
Measured vortex formation frequency (measuring vortex formation if there are over 2 times rotations)	0.22 Hz

- Assumption of Karman equation induce the difference between predicted and measured vortex formation frequency: predicted vortex formation frequency is higher than measured one
  - ✓ Steady flow
  - ✓ No vortex definition (size, vorticity, strength)
  - ✓ Infinite flow surface

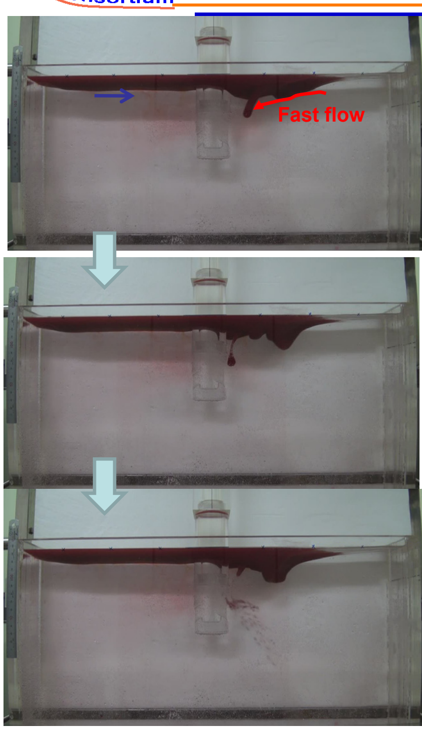
Slag Entrainment with Asymmetric Flow



<No-Clog Case> <Severe-Clog Case>

- Vortex formation and shear instability induced by asymmetric flow can entrain slag

Slag Entrainment by Shear Instability



< Small entrainment >

< Large entrainment >

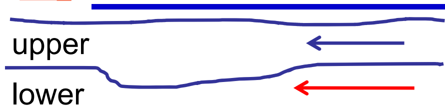
- Abnormal fast surface flow induce instability of layer between oil and water, resulting in entrainment of oil into water pool

- Entrained oil reaches nozzle port

- Jet flow takes oil deep into the mold
- Oil is decomposed into small size

What decide the quantity of entrained oil?

Application of Equations to Predict Critical Velocity for Shear Instability



$$\Delta V_{crit,min} = \sqrt[4]{4g(\rho_l - \rho_u)\Gamma_{ul}\left(\frac{1}{\rho_l}+\frac{1}{\rho_u}\right)^2}$$

< Von Helmholtz, H.L.F.: Uber discontinuierliche FlueBigkeits-Bewegungen; Monatsb. K. Preuss. Akad. Wiss. Berlin, 23 (1868), P. 215-228 >

< Thomson, W. (Lord Kelvin): Hydrokinetic Solutions and Observations; Phil. Mag., 42 (1871), No. 281, P. 362-377>

$$\Delta V_{crit,min} = \sqrt[4]{4g(\rho_l - \rho_u)\Gamma_{ul}\frac{(\mu_l+\mu_u)^4}{(\rho_u\mu_l^2+\rho_l\mu_u^2)^2}}$$

< T. Funada and D. D. Joseph, Journal of Fluid Mechanics 445 (2001), p. 263-283 >

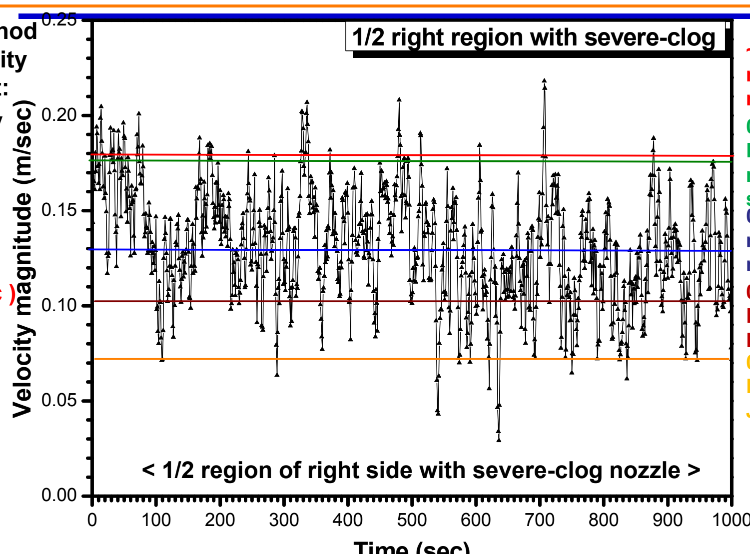
	Theory	Application
$\Delta V_{crit,min}$	Critical minimum velocity difference between two layers	**Kelvin-Helmholtz: 0.072** m/sec **Funada-Joseph: 0.102** m/sec
g	Gravitational acceleration	9.8 m/sec^2
ρ_l	Density of lower liquid	Water: 998 kg/m^3
ρ_u	Density of upper liquid	Silicon Oil: 965 kg/m^3
Γ_{ul}	Interfacial tension between two liquid	Silicon oil / water: 0.02 N/m
μ_l	Viscosity of lower liquid	Water: 0.001 $kg/m\cdot sec$
μ_u	Viscosity of upper liquid	Silicon Oil: 0.0965 $kg/m\cdot sec$

Comparison of Critical Velocity for Shear Instability and Entrainment between Predicted and Measured One

Measuring method of critical velocity for entrainment:

Critical velocity which includes 17 data points

(Entrainment occur 3 times during 180 sec → 17# /1000sec)



~0.180 m/sec: measured critical velocity magnitude for entrainment

0.175 m/sec: Predicted critical velocity magnitude by Hibbeler's simulation*

0.130 m/sec: mean velocity magnitude

0.102 m/sec: Kevin-Helmholtz

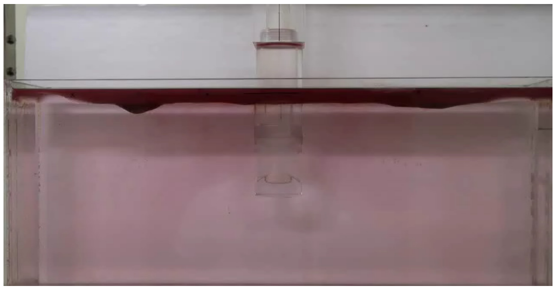
0.072 m/sec: Funada and Joseph

Predicted critical velocity magnitude for shear instability

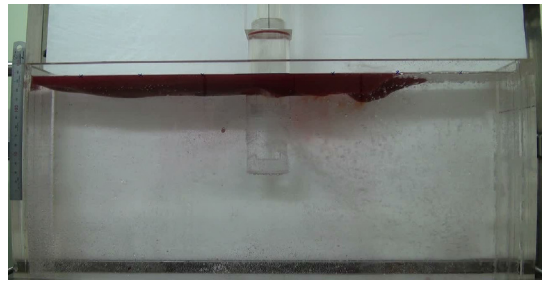
- **Critical velocity for entrainment is higher than reported eqs of critical velocity for shear instability**
- **Hibbeler's simulation results well-match with measured, so has excellent potential for future work.**
- **Funada-Joseph equation considering oil viscosity effect predicts lower critical velocity than Kevin-Helmholtz.**

* Lance Hibbeler, AISTECH 2010

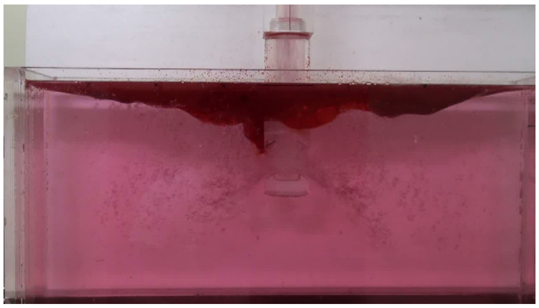
Effect of Argon Gas on Entrainment



< Argon gas flow rate: 0 SLPM >



< Argon gas flow rate: 0.6 SLPM >



< Argon gas flow rate: 1.8 SLPM >

- In spite of injected argon gas effect on decreasing effect of interfacial tension between oil and water and oil viscosity, shear instability could be decreased with optimizing argon gas injection conditions by decreasing surface velocity.
- Argon gas injecting over optimized conditions (flow rate and bubble size) could induce slag crawling with argon gas foaming in the oil layer.

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

	Mold flux (*)	Silicon oil
Density (g/ml)	3	0.965
Kinematic Viscosity (mm^2/s)	27~300 (at 1300°c)	100 (at 25°c)
Surface tension (mN/m)	250~375	20.9
Interfacial tension (mN/m)	1206~1285 (with steel)	20 (with water)

* Keiji Watanabe et al., ISIJ Int., Vol. 49 (2009), P. 1161-1166

	Steel	Water
Density (g/ml)	7.02	0.998
Kinematic Viscosity (mm^2/s)	0.855	1.00

Ratio of density:

$$\frac{\text{Density of liquid mold flux}}{\text{Density of molten steel}} = \frac{3}{7.02} = 0.43 < \frac{\text{Density of silicon oil}}{\text{Density of water}} = \frac{0.965}{0.9982} = 0.967$$

- Higher density ratio, lower interfacial tension and lacking viscosity gradient all produce more slag entrainment in silicon oil/water system than in steel/slag system
- It is need to understand entrainment phenomena in oil/water system and develop computational model for mold flux/steel system modeling

Summary - 1

- **Transient asymmetric flow with nozzle clogging**
  - Asymmetric jet from clogged nozzle cause asymmetric flow and unbalanced double roll pattern in the 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 and consistent flow at the gap between SEN and mold.
  - Transient mold flow by time induces complex roll pattern at mold upper regions, resulting in transient asymmetric flow at the surface.

- **Vortex formation and Slag Entrainment**
  - Asymmetric surface flow induced by turbulent flow variations and nozzle clogging makes vortices at 4 general regions near SEN.
  - Vortex frequency increases with clogging due to greater diff. of right/left velocity.
  - Karman vortex-prediction equation needs calibration to include transient flow, duration, and severity of the vortex.
  - Videos show slag entrainment from vortex formation, excessive transient surface velocity, and slag crawling down SEN

Summary - 2

  - Abnormal fast surface flow over critical velocity entrain slag by making severe shear instability.
  - There will be critical argon flow rate for entrainment by crawling.
  - It is need to understand entrainment phenomenon in oil/water system and develop computational model for mold flux/steel system modeling via modeling oil/water system of water model.

- **Comparison of SKE and Filtered URANS model with measurement.**
  - SKE model predicts the symmetric flow pattern with no clogging ok, but over-predicts the asymmetric suppression of surface flow by the faster flow in clogged cases.
  - Vortexing flow can be roughly calculated by steady SKE model.
  - Filtered URANS model has better capability to predict transient asymmetric flow and vortex formation.

Acknowledgements

- Continuous Casting Consortium Members (ABB, Arcelor-Mittal, Baosteel, Tata, Magnesita Refractories, Nucor Steel, Nippon Steel, POSTECH, POSCO, SSAB, ANSYS-Fluent)

- Dr. Rajneesh Chaudhary, Lance Hibbeler and Dr. Ho-Jung Shin

- Rui Liu for post processing of video

- Dr. Joo-Choi, Dr. Joong-Gil Park, Dr. Shin-Eon Kang and Sang-Woo Han (POSCO Technical Research Laboratories)

- POSCO (Grant No. 4.0006378.01)

- The National Science Foundation (Grant No. DMI 07- 27620)