ANNUAL REPORT 2009

UIUC, August 5, 2009

Misalignment Effects on Vortex Formation

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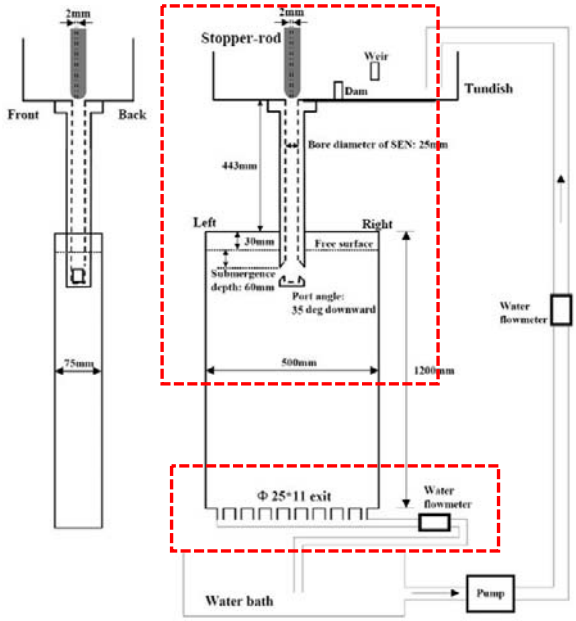
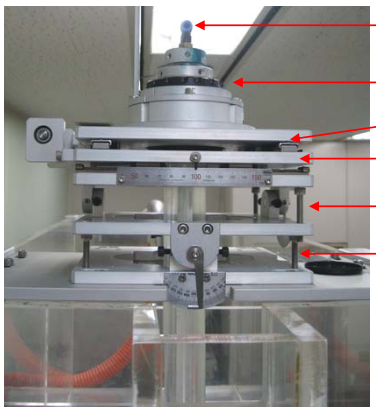
Research Scope

- Vortex formation can entrap mold flux and cause defects in slab casting.
- Objective: study effect of stopper rod asymmetry on vortex formation, using math and physical models.
- Simulation results show vortices near SEN with misaligned stopper-rod.
- Water model experiments quantify vortex formation to verify simulation results, and evaluate Karman vortex equation for frequency, and penetration depth equation.

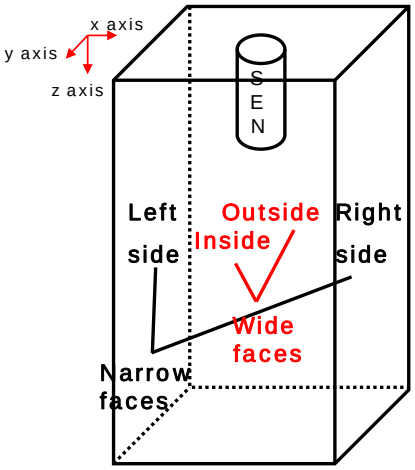
Schematic of 1/3 Scale Water Model



Control System to Change Stopper-rod Location



< Side view of stopper-rod system >

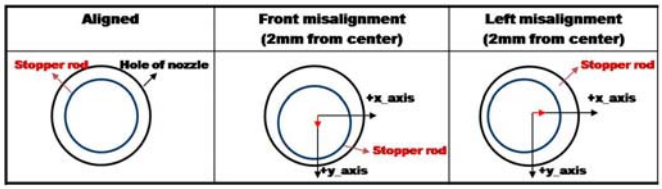


< Front view >

X axis movement: Misalignment toward narrow faces

Y axis movement: Misalignment toward wide faces

Z axis movement: Movement for controlling flow rate



< Top view >

Processing Conditions for Experimental and Computational Works

Casting speed	0.917 m/min
Water flow rate	34.4 LPM
Mold width	500 mm
Mold thickness	75 mm
Computational domain width	250 mm
Computational domain thickness	37.5 mm
Computational domain length	1200 mm
SEN depth	60 mm
ρ_{fluid}	998.2 kg/m^3 (water)
μ_{fluid}	0.001003 kg/m-s (water)
Stopper-rod location	Aligned(Center) 2mm misaligned(Front and Left)
Nozzle(well bottom type) port angle	35 degree
Nozzle port area	23.3 mm(width) x 26.7mm(height)
Nozzle bore diameter (inner/outer)	25 mm/43 mm
Distance between tundish bottom and nozzle bottom	560 mm
Shell	no
Gas injection	no

Experimental Approach

Visualization of vortex formation:

- **Scatter sesame seeds(tracer particles) at surface of water-model mold**
- **Record high speed videos and take pictures**

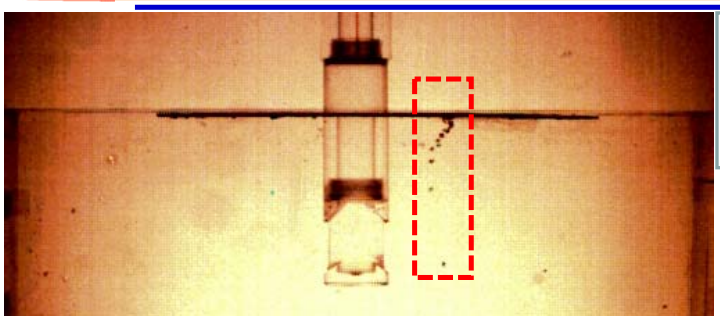
Measuring vortex frequency:

- **Count number and location of vortices in a time interval**
- **Divide number of vortex at each location by the time interval**

Analyzing velocity profiles:

- **Measure velocity profiles near surface with impeller flow probe**
- **Compare velocity profiles on left / right sides and NF / center**
- **Calculate asymmetric flow fractions, average velocities, velocity variations, turbulent kinetic energy(K)**

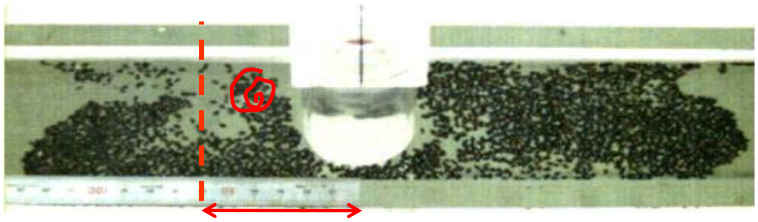
Visualization of Vortex(1)



Duration time of vortex formation:
- Most vortex : 2~3sec
- Strong vortex that can trap the seeds: 5~7sec

Maximum depth of vortex from surface: down to 70mm

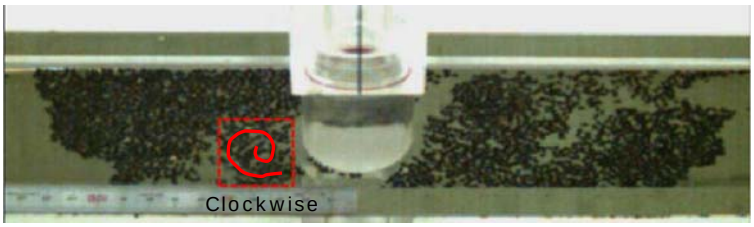
- Some vortices trap the seeds(tracer particles) : Vortex could be the cause of entrapment of real caster



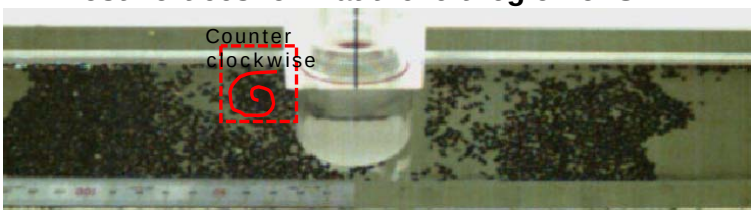
60mm

- Most vortices were formed within 60mm from center of SEN

Visualization of Vortex(2)

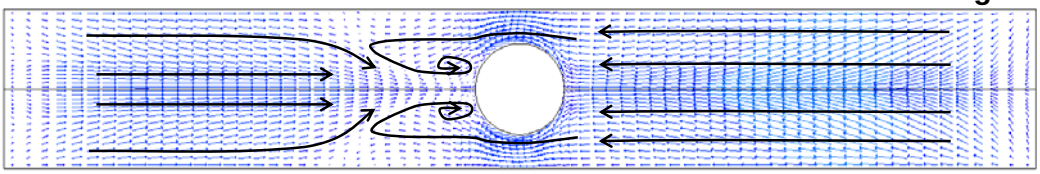


< Most vortices form at the left region of SEN >

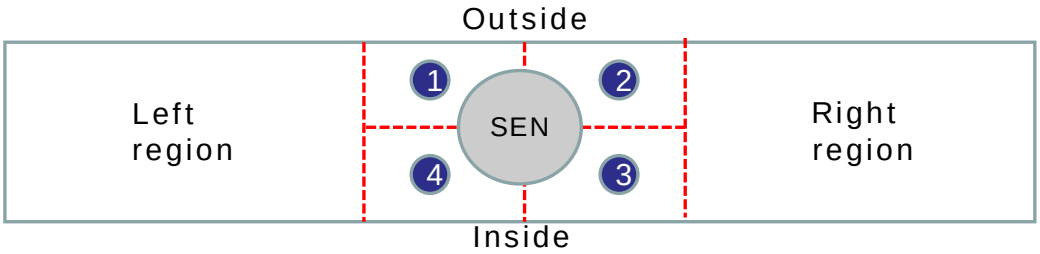


Left

Right



Method of Counting Vortex Formation



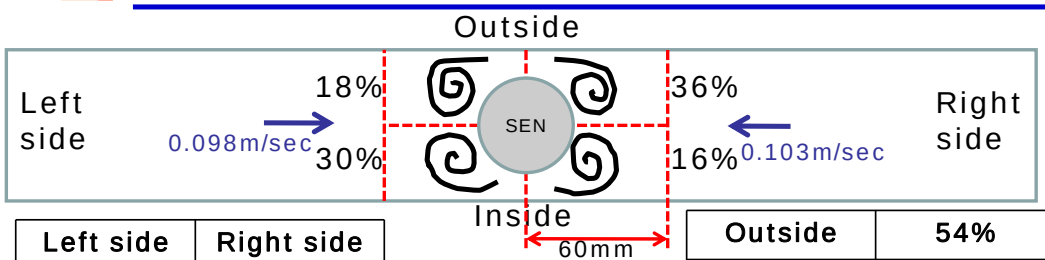
Counting vortex formation

- **Divide the four region near SEN**
- **Count the number of each region in a time interval**

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

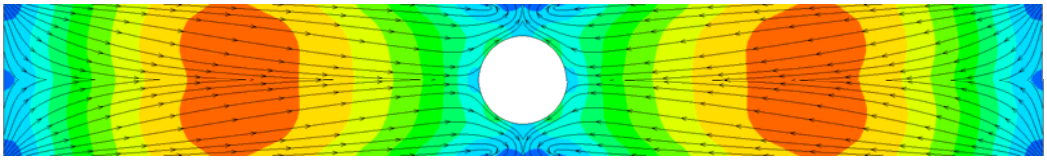
Outside region VS Inside region : 1 + 2 VS 3 + 4

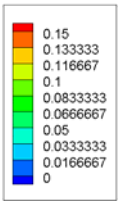
Vortex Location Fraction
(Aligned)



Left side	Right side
48%	52%

Outside	54%
Inside	46%



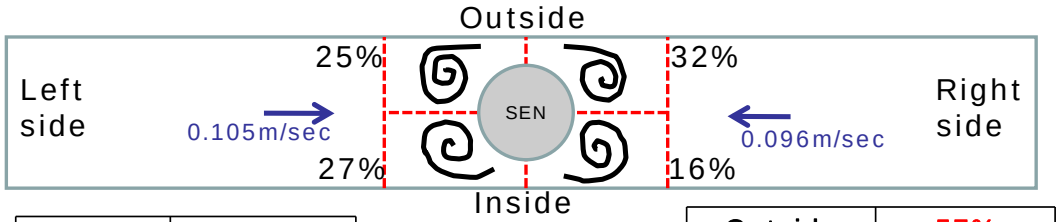


Velocity magnitude(m/sec)

-Asymmetry of vortex location fraction is small with aligned stopper-rod

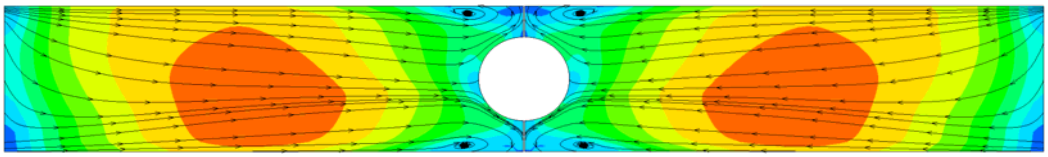
-Transient flow make the vortex in a water model

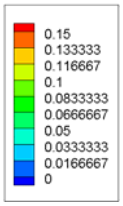
Vortex Location Fraction
(Front misaligned)



Left side	Right side
52%	48%

Outside	57%
Inside	43%



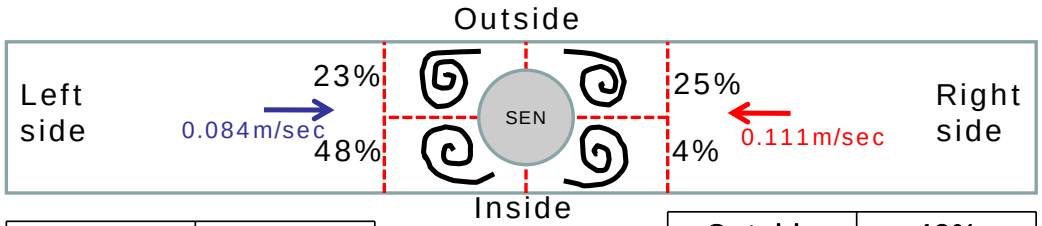


Velocity magnitude(m/sec)

- Asymmetry of vortex location fraction between inside and outside in a water model

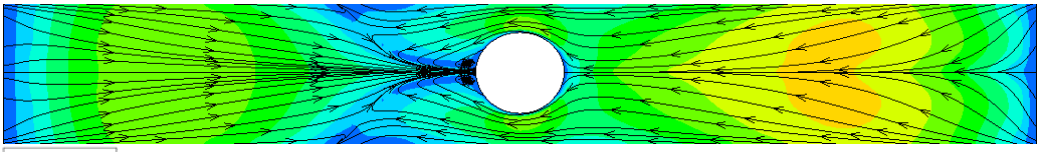
-Asymmetry of vortex location fraction between left and right is small

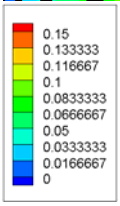
Vortex Location Fraction
(Left misaligned)



Left side	Right side
71%	29%

Outside	48%
Inside	52%



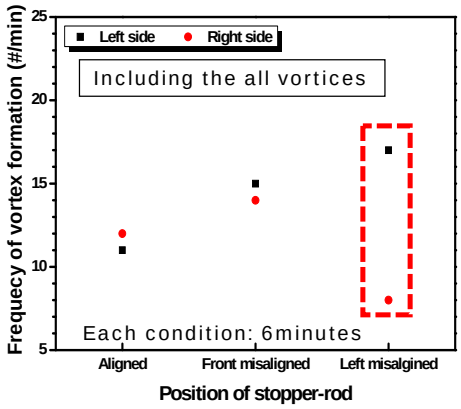


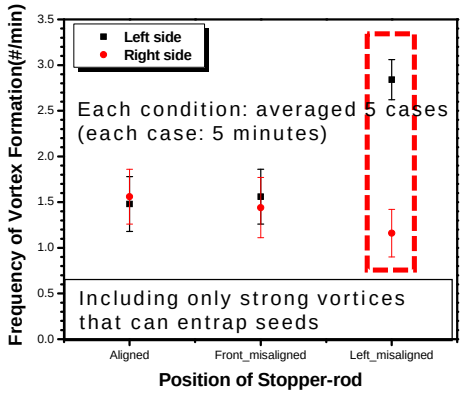
Velocity magnitude(m/sec)

- More vortices form at the left region of SEN

- Asymmetry of vortex location fraction between inside and outside is small

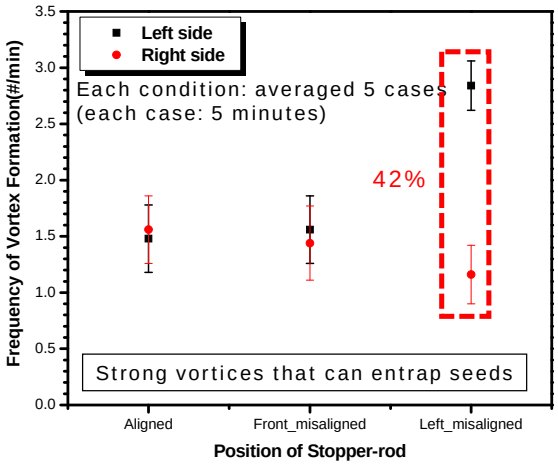
Asymmetry of Vortex Formation Frequency(1)

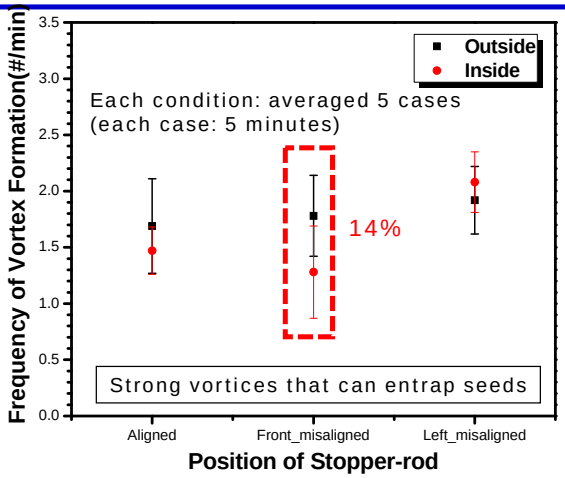




- More and strong vortices form at the left region of SEN with left misaligned stopper-rod

Asymmetry of Vortex Formation Frequency(2)

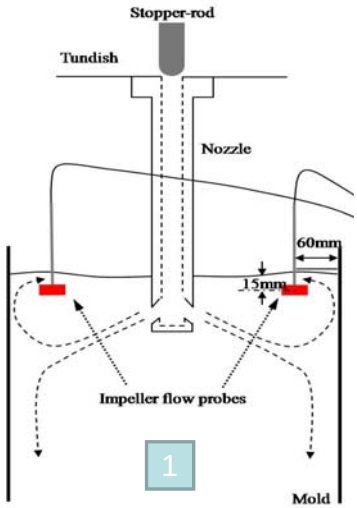


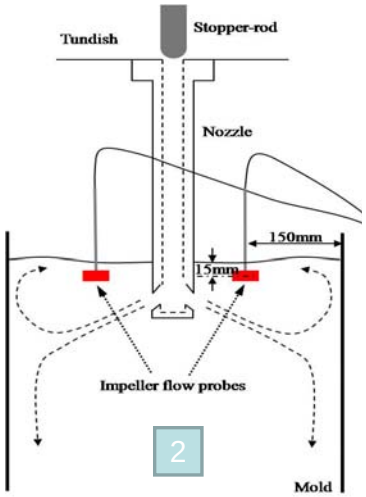


Vortex Formation Ratio (%)		Left region	Right region
Aligned		48	52
Misaligned (2mm)	Front	52	48
	Left	71	29

Vortex Formation Ratio (%)	Aligned	Misaligned (2mm)	
		Front	Left
Outside	54	57	48
Inside	48	43	52

Measuring Velocity Magnitude by Impeller

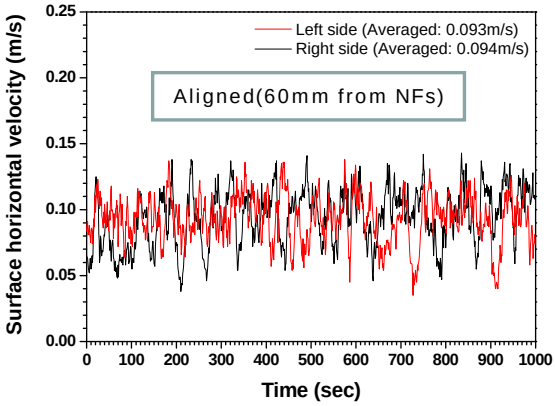


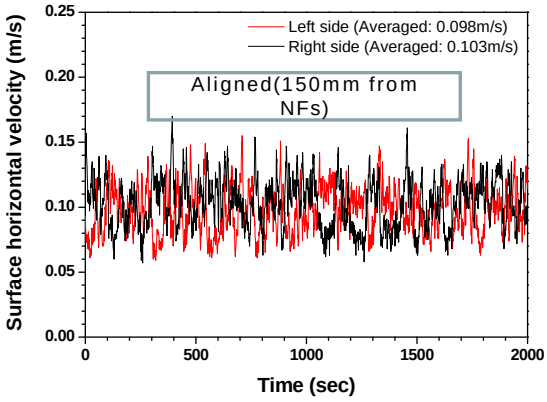


15mm away from free surface
60mm away from NF
Measuring time: 1000sec

15mm away from free surface
150mm away from narrow faces
Measuring time: 2000sec

Analysis of Surface Horizontal Velocity Profiles(1)

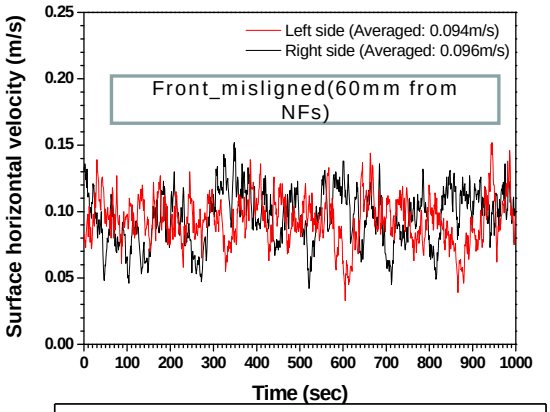


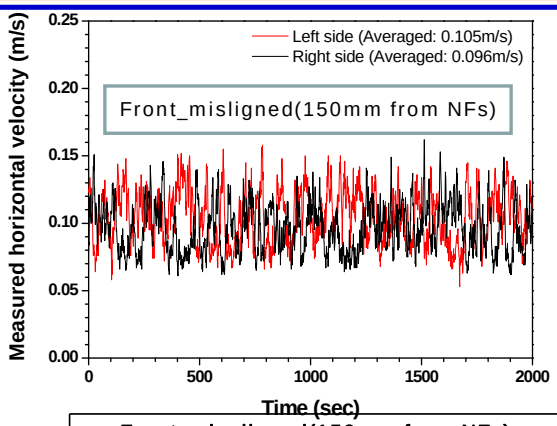


Aligned(60mm from NFs)		
Total data point:1000	R<L	R>L
# of data points (asymmetric fraction,%)	492 (49%)	508 (51%)
Avg_variation (between left and right) (m/sec)	0.023	0.025
Max_variation (m/sec)	0.071	0.07

Aligned(150mm from NFs)		
Total data point:2000	R<L	R>L
# of data points (asymmetric fraction,%)	878 (44%)	1122 (56%)
Avg_variation (between left and right) (m/sec)	0.024	0.029
Max_variation (m/sec)	0.071	0.093

Analysis of Surface Horizontal Velocity Profiles(2)

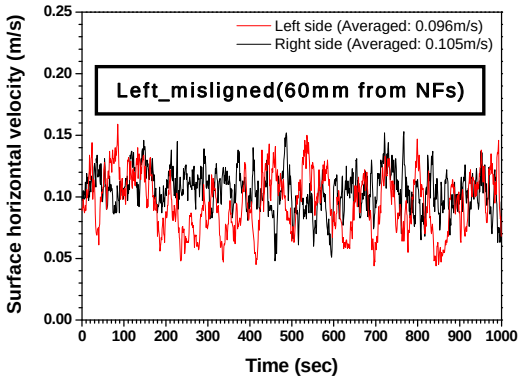


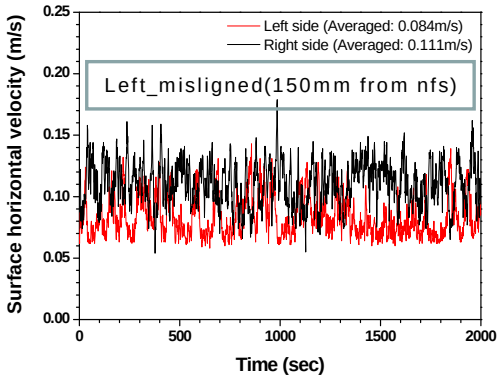


Front_misaligned(60mm from NFs)		
Total data point:1000	R<L	R>L
# of data points (asymmetric fraction %)	477 (47.5%)	523 (52.5%)
Avg_variation (between left and right) (m/sec)	0.024	0.026
Max variation (m/sec)	0.069	0.086

Front_misaligned(150mm from NFs)		
Total data point:2000	R<L	R>L
# of instances (asymmetric fraction%)	1175 (58.5%)	825 (41.5%)
Avg_variation (between left and right) (m/sec)	0.031	0.022
Max variation (m/sec)	0.091	0.087

Analysis of Surface Horizontal Velocity Profiles(3)





Left_misaligned(60mm from NFs)		
Total data point:1000	R<L	R>L
# of data points (asymmetric fraction%)	361 (36.5%)	639 (63.5%)
Avg_variation (between left and right) (m/sec)	0.022	0.027
Max variation (m/sec)	0.09	0.089

Left_misaligned(150mm from NFs)		
Total data point:2000	R<L	R>L
# of data points (asymmetric fraction%)	365 (18.5%)	1635 (81.5%)
Avg_variation (between left and right) (m/sec)	0.017	0.037
Max variation (m/sec)	0.066	0.113

Comparison of measured Vortex frequency with Surface velocity (avg, max, variations, and asymmetric fraction)

Aligned(150mm from nfs)		
Total data point:2000	R<L	R>L
# of data points(total:2000) (asymmetric fraction%)	878 (44%)	1122 (56%)
Avg_variation (between left and right) (m/sec)	0.024	0.029
Max variation (m/sec)	0.071	0.093

Left_misaligned(150mm from nfs)		
Total data point:2000	R<L	R>L
# of data points(total:2000) (asymmetric fraction%)	365 (18.5%)	1635 (81.5%)
Avg_variation (between left and right)(m/sec)	0.017	0.037
Max variation (m/sec)	0.066	0.113

Front_misaligned(150mm from nfs)		
Total data point:2000	R<L	R>L
# of data points(total:2000) (asymmetric fraction%)	1175 (58.5%)	825 (41.5%)
Avg_variation (between left and right)(m/sec)	0.031	0.022
Max variation (m/sec)	0.091	0.087

Measured vortex frequency(#/min)		Left region		Right region	
		all	strong	all	strong
Aligned		11	1.48	12	1.56
Misaligned	Front (2mm)	15	1.56	14	1.44
	Left (2mm)	17	2.84	8	1.16

- Left misaligned: Vortex frequency and asymmetry are higher when right side velocity is faster than left (as indicated by higher avg., max., variation, and asymmetric fraction on right, which are always consistent).

- Asymmetric flow could make more vortices and strong vortices near left region of SEN with left misaligned stopper-rod

Comparison of Measured Vortex Frequency with Turbulent Kinetic Energy and Averaged Velocity Magnitude of Measurement

Turbulent Kinetic Energy(m2/sec2) (150mm away from NF)					
		Left region (*e-04 m2/sec2)		Right region (*e-04 m2/sec2)	
		predicted	measured	predicted	measured
Aligned		3.75	4.72	3.75	5.30
Misaligned	Front	5.33	5.52	5.33	5.07
	Left	1.40	4.04	3.00	4.88

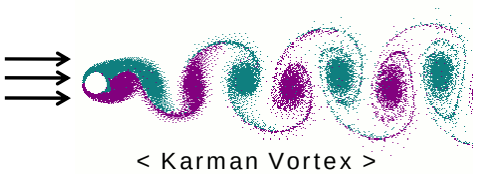
Measured Average Velocity(m/sec) (150mm away from NF)			
		Left region	Right region
Aligned		0.098	0.103
Misaligned	Front	0.105	0.096
	Left	0.084	0.111

Measured vortex frequency(#/min)		Left region		Right region	
		all	strong	all	strong
Aligned		11	1.48	12	1.56
Misaligned	Front (2mm)	15	1.56	14	1.44
	Left (2mm)	17	2.84	8	1.16

-Asymmetric turbulent kinetic energy and velocity between left region and right region both influence the asymmetric surface flow and vortex formation

- Difference of surface flow velocity is more direct cause of vortex formation

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

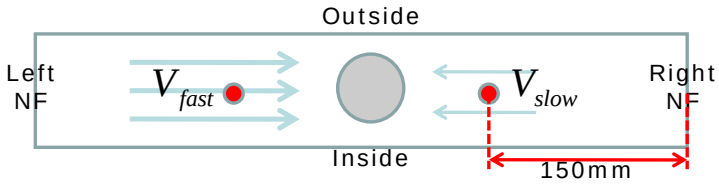


< Karman Vortex >

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

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

< Water model>



	Theory	Application	
f	vortex frequency(#/sec)		
d	Diameter of the cylinder(m)	Diameter of the SEN(0.043m)	
V	Velocity of the flow toward the cylinder(m/sec)	$V' = V_{fast} - V_{slow}$	Variation of measured surface velocity between left and right(m/sec)
ν	Kinematic viscosity of the fluid(m2/sec)	Kinematic viscosity of water ($1.004\times10^{-6} m^2/s$)	

Application of Karman Vortex Equation to Measured Surface Velocity in a 1/3 Water Model(2)

Theory: the formula will hold true for the range ($250 < \mathrm{Re} < 2\times10^5$)

↓

Application: available range of $V' = V_{fast} - V_{slow}$ for the frequency equation ($0.006 m/\sec < V' < 4.67 m/\sec$)

↓

Application to measured velocity in a water model

$$f = \frac{0.198(Vd - 19.7\nu)}{d^2} \longrightarrow f = 4.6V' - 0.0021$$

Calculations with Karman Vortex Equation

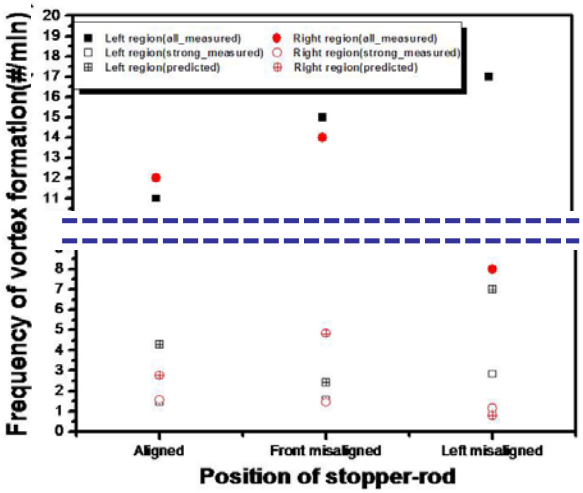
Predicted vortex frequency using average velocity			
	Left (m/sec)	Right (m/sec)	Vortex frequency(#/min)
Aligned	0.098	0.103	0.30(left region)
Front misaligned	0.105	**0.096**	0.54(right region)
Left misaligned	0.084	0.111	1.62(left region)

-Average velocity predicts vortices on only one side; but measurements show both sides.
-Instead:
-Vortices are caused by small left-right velocity variations
- Instantaneous velocity is better v for predicting vortex formation

Predicted vortex frequency using Instantaneous velocity		
	Left region_ vortex Frequency (#/min)	Right region_ vortex Frequency (#/min)
Aligned	4.28	2.76
Front misaligned	2.42	4.83
Left misaligned	6.99	0.79

Measured vortex frequency(#/min)		Left region		Right region	
		all	strong	all	strong
Aligned		11	1.48	12	1.56
Misaligned	Front (2mm)	15	1.56	14	1.44
	Left (2mm)	17	2.84	8	1.16

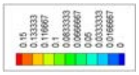
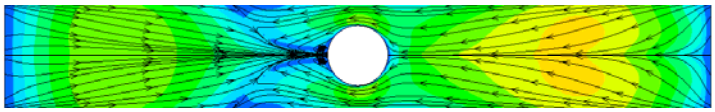
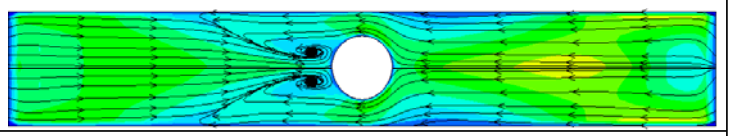
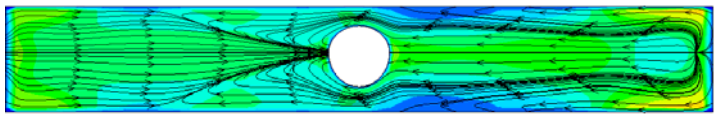
Comparison of Measured Vortex Frequency with Predicted One by Karman vortex frequency equation

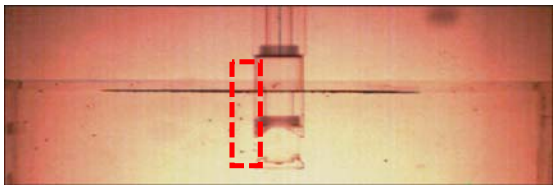


- Asymmetry of vortex formation location is high with a left-misaligned stopper-rod (There are more vortices at left region of SEN with a left-misaligned stopper-rod).

- Predicted vortex frequency is between measured frequency of all vortices and strong vortices. (Karman vortex equation over-predicts number of strong vortex)

Penetration of Vortex

	Velocity magnitude (m/sec) **Penetration of Vortex with Left-misaligned stopper-rod**
Free Surface	
30mm from Free Surface	
50mm from Free Surface	



- Vortex expand and move toward NF along the 30mm depth from free surface.
- Vortex become extinct at the depth near SEN port.
- The penetration of vortex in a water model is deeper than simulation results

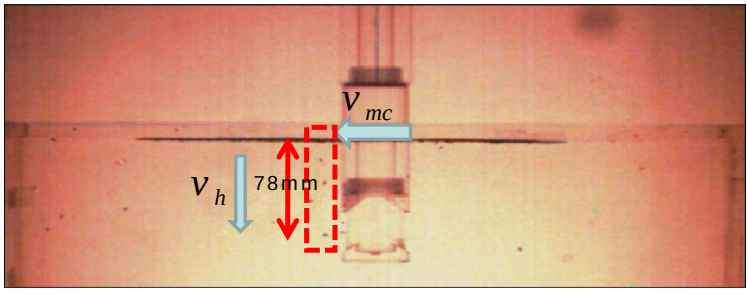
Evaluation of Equation to predict Vortex Penetration Depth
(application to left misaligned stopper-rod case)

$$D_v = \frac{\rho_w}{\rho_w - \rho_p}\frac{v_{mc}^2}{g} + 0.654\left\{\frac{\rho_p \Delta v_h^2}{2g(\rho_w - \rho_p)}\right\}^{0.55}$$

Assumption: the kinetic energy of model mold powder = the work done by the buoyancy

< Norifumi KASAI and Manabu IGUCHI, ISIJ Int, Vol. 47(2007), No. 7, pp. 982-987 >

D_v	penetration depth of vortex
ρ_w	Density of water (998.2kg/m3)
ρ_p	Density of mold powder(seeds: 886.8kg/m3)
v_{mc}	Horizontal velocity in the region between the SEN and WFS(0.029m/sec)
Δv_h	Sudden decrease of vertical velocity(0.026m/sec)



D_v	Measured	78 mm
	Predicted by the equation	8 mm

- Turbulent kinetic energy, vorticity could be more important factors on vortex penetration depth

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Conclusions

Measurement and Simulation:

- Averaged surface horizontal velocity and turbulent kinetic energy by measurement match quite well with predicted results of R. Chaudhary
- Most vortices are formed at 4 regions near SEN (60mm from SEN center)
- Misaligned stopper-rod causes asymmetric vortex formation
  * Most vortices form at the left region of SEN with left misaligned stopper-rod (matched with simulation results of R. Chaudhary)
  * Vortices form more at the outside region than inside region with front misaligned stopper-rod
- Vortices are caused by the difference of flow velocity between right and left side
- Vortices are stronger and more frequent with big right/left velocity difference
- The simulation predicts vortex formation similar to observations in water model but predicted location is slightly closer to centerline, and has shallower penetration and different shape.

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Conclusions

Measurement and Previous Theoretical Equations

1) Karman Vortex Formation

- Predictions using instantaneous velocity matches observed vortex formation trends. The predictions fall in between strong and weak vortex frequency measurements.
- Quantitative agreement depends on subjective opinion of vortex strength.
- Strong vortices (able to entrain slag) are more relevant to commercial practice.
- Karman equation with instantaneous velocity seems to be fundamentally sound and predicts correct trends (needs calibration for vortex strength)

2) The penetration depth equation (KASAI and IGUCHI)

- The penetration depth equation of KASAI and IGUCHI greatly underpredicts the measurements. Perhaps should consider turbulent kinetic energy & vorticity.

Acknowledgements

-Continuous Casting Consortium Members (ABB, Arcelor-Mittal, Baosteel, Corus, Delavan/Goodrich, LWB Refractories, Nucor, Nippon Steel, Postech, Steel Dynamics, ANSYS-Fluent)

-POSCO: An Jong Tae, Ho Jung Shin

-Technology Innovation Center for Metals & Materials at POSTECH for high speed camera

- POSTECH: Hyun Na Bae, Hyoung Jun Lee, See young Park