CCC Annual Report
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Effect of Nozzle Port Angle on Mold Flow

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Research Scope

- **Objectives**:
  - **Optimize nozzle port angle** to reduce flow-related surface defects in wide slab
  - **Investigate mold flow patterns** in wide slab caster with current casting conditions
  - **Quantify effect of nozzle port angle** on flow pattern and surface velocity, and surface level in a wide slab caster
  - Investigate similarity between water model experiments and plant measurements by comparing surface velocity
- **Methodologies**:
  - **1/3 scale water model experiments** to visualize mold flow patterns and quantify surface velocity and surface level fluctuations
  - **Plant measurements** to measure surface velocity, surface level, slag pool thickness using nail dipping tests and level sensor measurements
  - **Computational modeling using Fluent on lab workstation or Blue Waters supercomputer** to quantify nozzle flow and mold flow

Caster Dimensions and Process Conditions

	Real STS caster (Case R)	Lab (1/3) scale Water model (Case W)
Casting speed	0.8 m/min	0.5 m/min
Volume Flow rate	256.0 LPM	16.4 LPM
Mold width	1600 mm	533 mm
Mold thickness	200 mm	67 mm
Aspect ratio between mold width and thickness	8.0	8.0
SEN depth	140 mm	46.7 mm
Nozzle port angle	**15° (up) degree**	**15° (up), 5°(up), -15° (down), -30° (down) degree**
Nozzle port size (width x height)	60 mm x 65 mm	20 mm x 21.7 mm
Nozzle bore (inner / outer)	ϕ 60 ~ 65 mm (from bottom to top) / ϕ 110 mm	ϕ20.8 mm (average) / ϕ36.6 mm
Area ratio between two ports and nozzle bore	2.54	2.54
Ar gas injection	No gas	10 ml/min (0.06 % volume fraction) **clear visualization of mold flows**

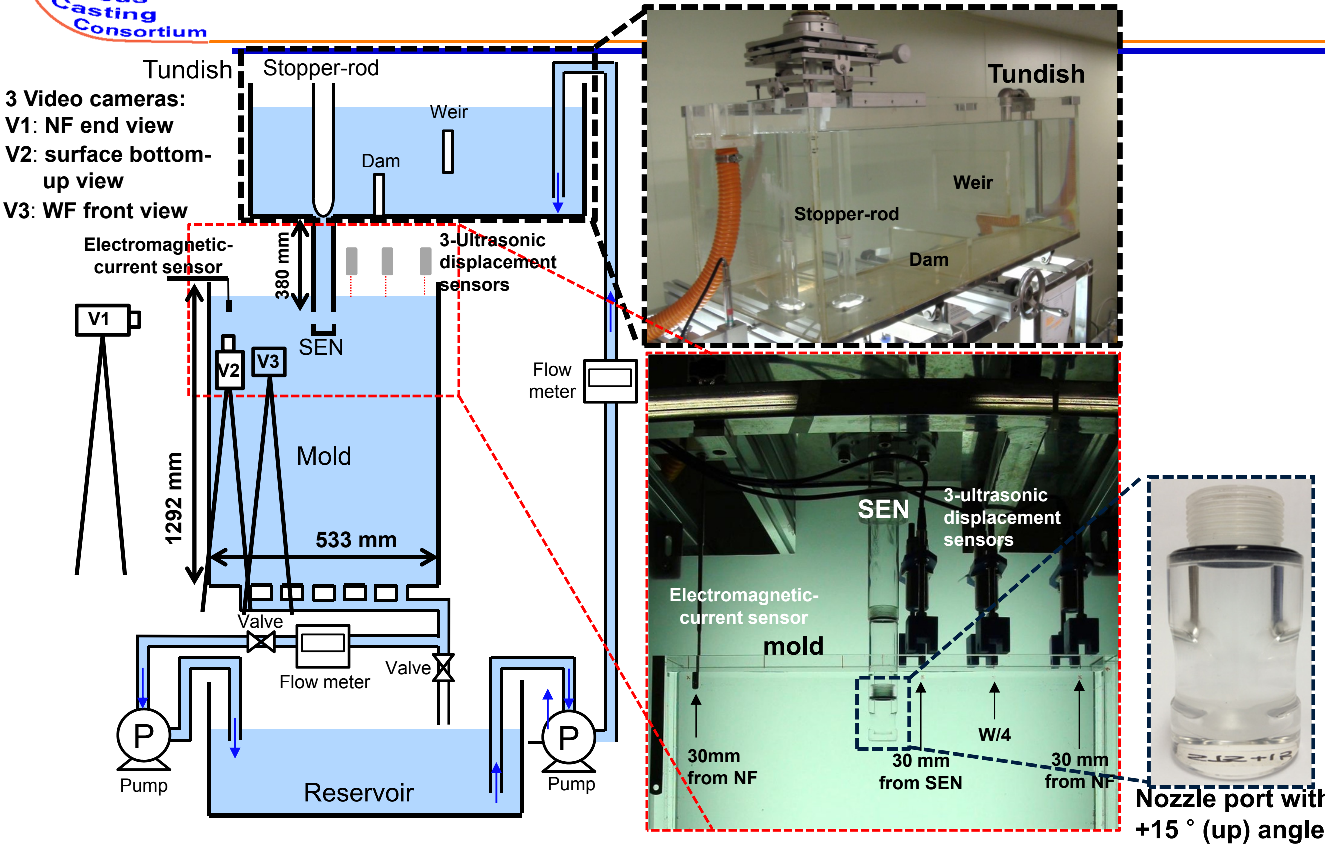
- Flow similarity between 1/3 scale water model (Case W) and real caster (Case R)
  - ➡ Froude number (ratio of inertia force to gravitational force): $\left(u/\sqrt{gL}\right)_W = \left(u/\sqrt{gL}\right)_R$

    Casting speed $u_{c,W}$ for 1/3 scale water model: $u_{c,W} = u_{c,R}\sqrt{L_W/L_R}$

Continuous Casting Consortium

Physical Water Model Experiments

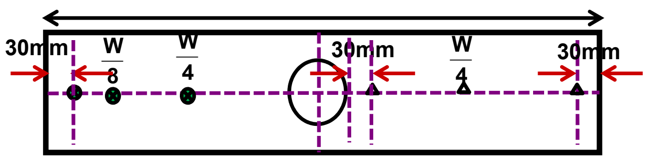
Schematic of 1/3 Scale Water Model



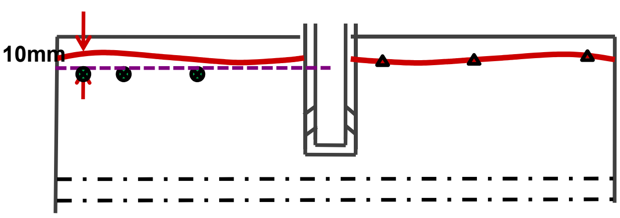
Electromagnetic Current Sensor (for Surface Velocities) and Ultrasonic Displacement Sensor (for Surface Level Variations) Measurements

Measuring positions of surface flow velocity and surface level

- ● : Electromagnetic current sensor measurement position
- ▲ : Ultrasonic displacement sensor measurement position



Top view / surface



Front view / wide face

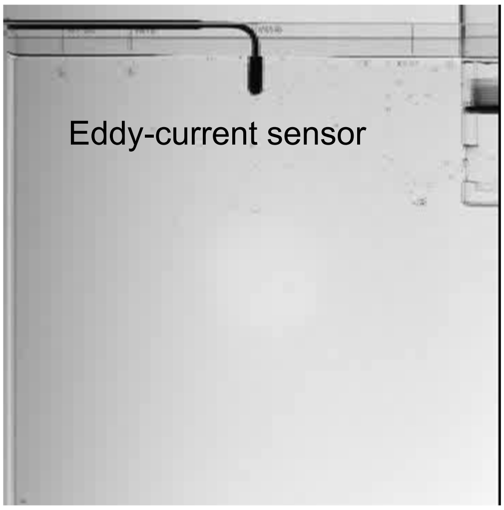
- Measure **transient surface velocity** at 10mm below surface on W/4, W/8, 30 mm from NF, using **electromagnetic current sensor** during 1000 sec.
- Measure **transient surface level** on 30mm from SEN, W/4, 30 mm from NF points, using **ultrasonic displacement sensors** during 1000 sec.

Videos to Visualize Mold Flow

<NF end view>

<Surface bottom-up view>

* Case W. +5 (up) angle nozzle port

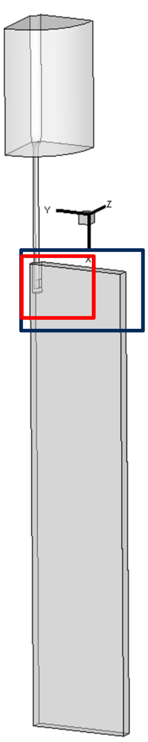
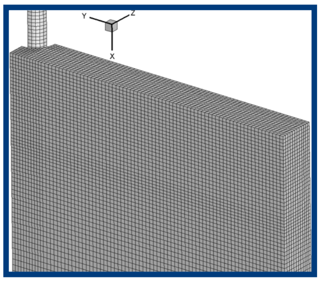
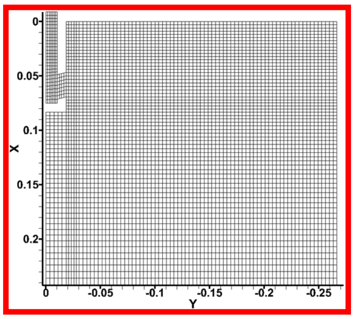


<WF front view>

- Record 3 videos to show both nozzle and mold flow at same time
- Understand measured surface velocity and surface level with help of recorded videos

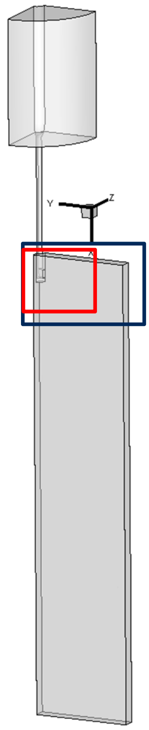
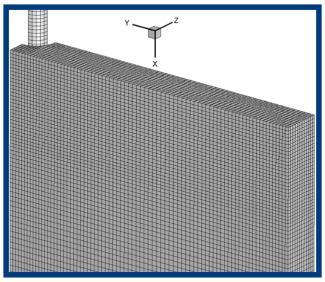
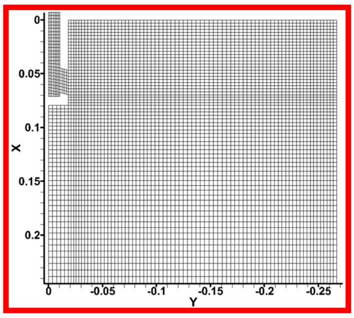
Modeling and Results Analysis

Quarter Domain and Mesh: Standard k-ε Flow Model with Fluent on Lab Computer (LC)

quarter domain: ~ 0.15 million hexahedral cells

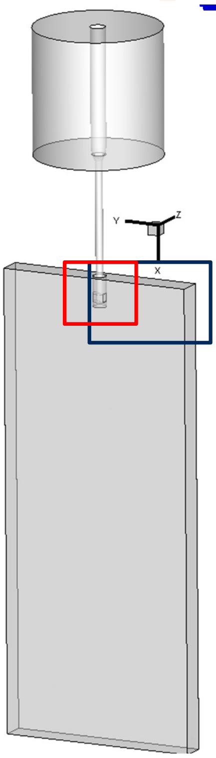
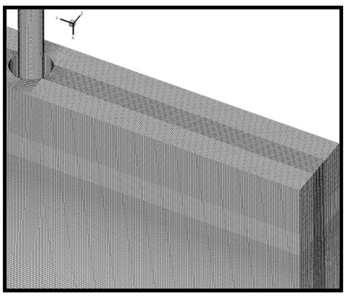
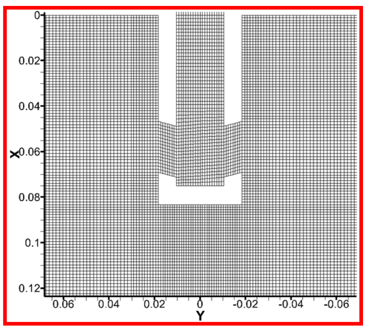
Case W-LC. +15° (up) angle nozzle

quarter domain: ~ 0.15 million hexahedral cells

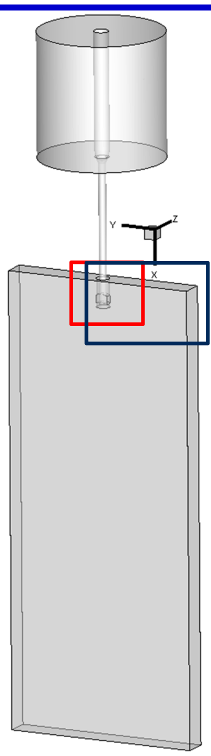
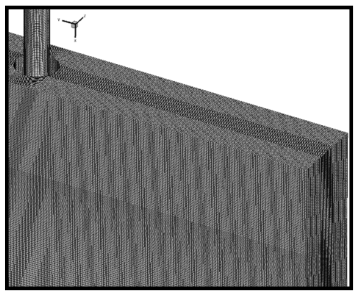
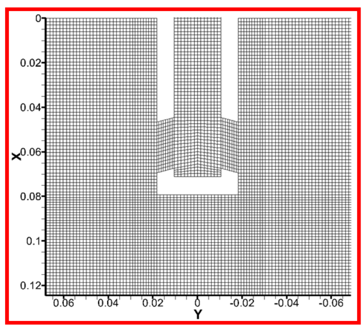
Case W-LC. -15° (down) angle nozzle

Full Domain and Mesh: LES with Fluent on Blue Waters (BW)

Full domain: ~ 2.4 million hexahedral cells

Case W-BW. +15° (up) angle nozzle

Full domain:~ 2.6 million hexahedral cells

Case W-BW. -15° (down) angle nozzle

Governing Equations

- **Case W-LC: Reynolds Averaged Navier-Stokes (RANS) Model with standard k-ε model**

$$\frac{\partial}{\partial x_i}\left(\rho\overline{u_i}\right)=0$$

Mass conservation

$$\frac{\partial}{\partial x_j}\left(\rho\overline{u_i}\,\overline{u_j}\right)=-\frac{\partial\overline{p}^*}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\left(\mu+\mu_t\right)\left(\frac{\partial\overline{u_i}}{\partial x_j}+\frac{\partial\overline{u_j}}{\partial x_i}\right)\right]$$

Momentum conservation

$$\frac{\partial}{\partial x_i}\left(\rho k\overline{u_i}\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon$$

Turbulent kinetic energy

$$\frac{\partial}{\partial x_i}\left(\rho\varepsilon\overline{u_i}\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

Turbulent kinetic energy dissipation rate

- **Case W-BW: Large Eddy Simulation (LES) with Wall-Adapting Local Eddy (WALE) subgrid-scale viscosity model**

$$\frac{\partial}{\partial x_i}\left(\rho u_i\right)=0$$

Mass conservation

$$\frac{\partial}{\partial t}\left(\rho u_i\right)+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial p^*}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\left(\mu+\mu_t\right)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]$$

Momentum conservation

$$\mu_t=\rho\left(L_S\right)^2\frac{\left(S_{ij}^d S_{ij}^d\right)^{3/2}}{\left(S_{ij}S_{ij}\right)^{5/2}+\left(S_{ij}^d S_{ij}^d\right)^{5/4}}$$

Turbulent viscosity

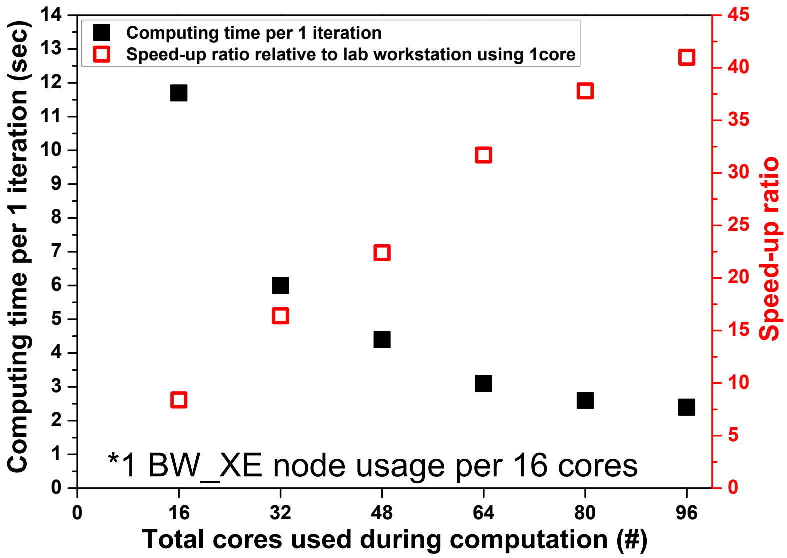
Boundary Conditions

	Case W-LC: Standard k-ε model	**Case W-BW: LES**
Inlet (Tundish bottom region)	Constant velocity: 0.00573 m/sec Turbulent kinetic energy: 10^{-5} m²/sec² Turbulent kinetic energy dissipation rate: 10^{-5} m²/sec³	Constant velocity: 0.0573 m/sec
Outlet (Mold exit)	Pressure: 0 pascal gauge pressure Turbulent kinetic energy for backflow: 10^{-5} m²/sec² Turbulent kinetic energy dissipation rate for back flow: 10^{-5} m²/sec³	Pressure: 0 pascal gauge pressure
Surface (interface between water and air)	Stationary wall with 0-shear stress	Stationary wall with 0-shear stress
Wide face, Narrow face, Stopper-rod, and Nozzle walls (interface between water and)	Stationary wall with no slip	Stationary wall with no slip

Fluent Performance on BW: Speed-Up Test

- **Test problem: Case W-BW**
  1/3 water model with 15º (up) nozzle ports
  Mesh of nozzle & mold: ~6.94 million hexahedral cells

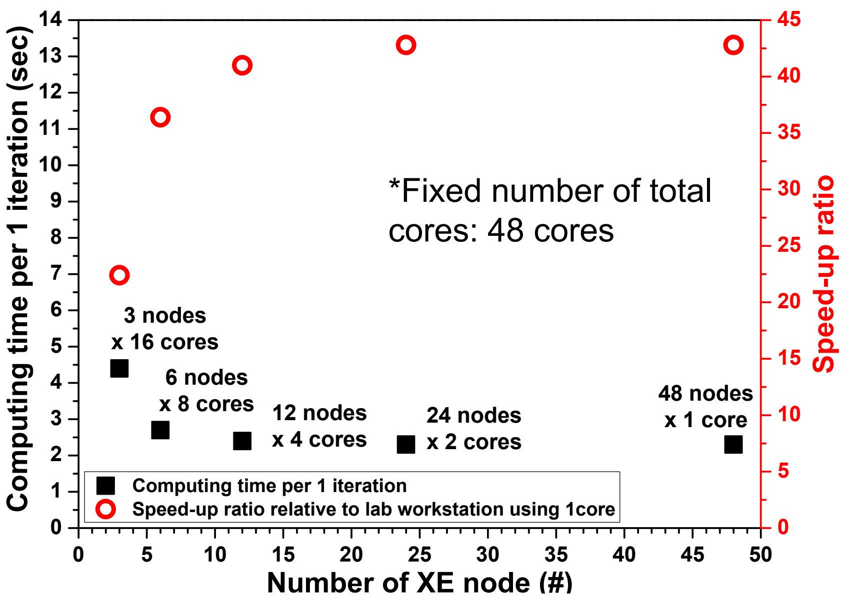
Speed-up ratio = Computing time per 1 iteration on LC / Computing time per 1 iteration on BW



<Speed up of FLUENT calculation on Blue Waters>

- With 96 cores (6 XE nodes), the simulation on Blue Waters runs ~ 41 times faster than on our Lab Computer (LC) (DELL Precision T7600 with Intel Xeon E5-2603 1.80 GHz CPU processor/node with 8 Cores): One iteration on Blue Waters using 96 cores (6 XE nodes) requires ~2.4 seconds of wall clock time. One the other hand, on the lab workstation (using 1 core), the same simulation requires ~ 98.4 seconds of wall-clock time per 1 iteration.
- Fluent computations on Blue Waters show almost linear speed-up with increasing XE nodes.

Fluent Performance on BW: Nodes-Cores Distribution Test

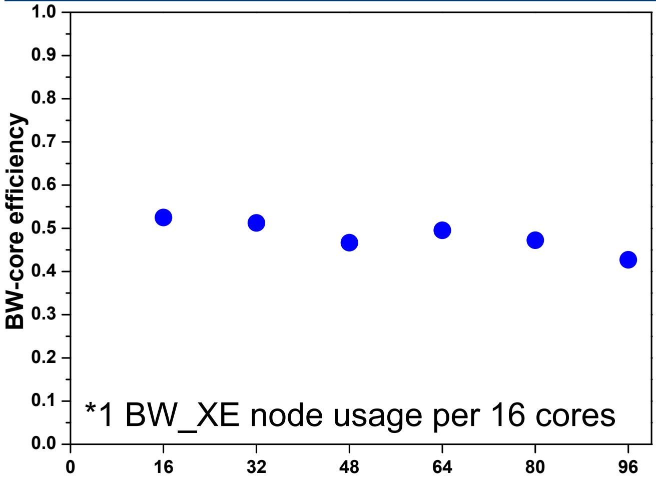


<Effect of distribution of nodes and cores on speed up of FLUENT calculation on Blue Waters>

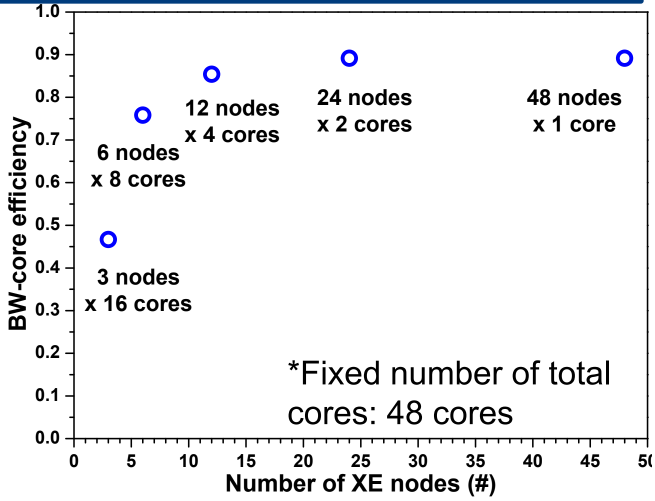
- For using same total cores (#48), speed-up of Fluent computation is more enhanced by increasing compute nodes.
- Applying the distribution of 48 nodes x 1 cores (total 48 cores), shows more speed-up (~43 times vs ~ 41 times) than using total 96 cores (6 nodes x 16 cores): 48 HPC licenses of the Ansys license pool can be saved with more speed-up.

Fluent Performance on BW: BW-Core License Efficiency

Blue Waters (BW)-core license efficiency = Speed-up ratio / total assigned cores = Computing time per 1 iteration on **LC / (**Computing time per 1 iteration on **BW x total assigned cores)**



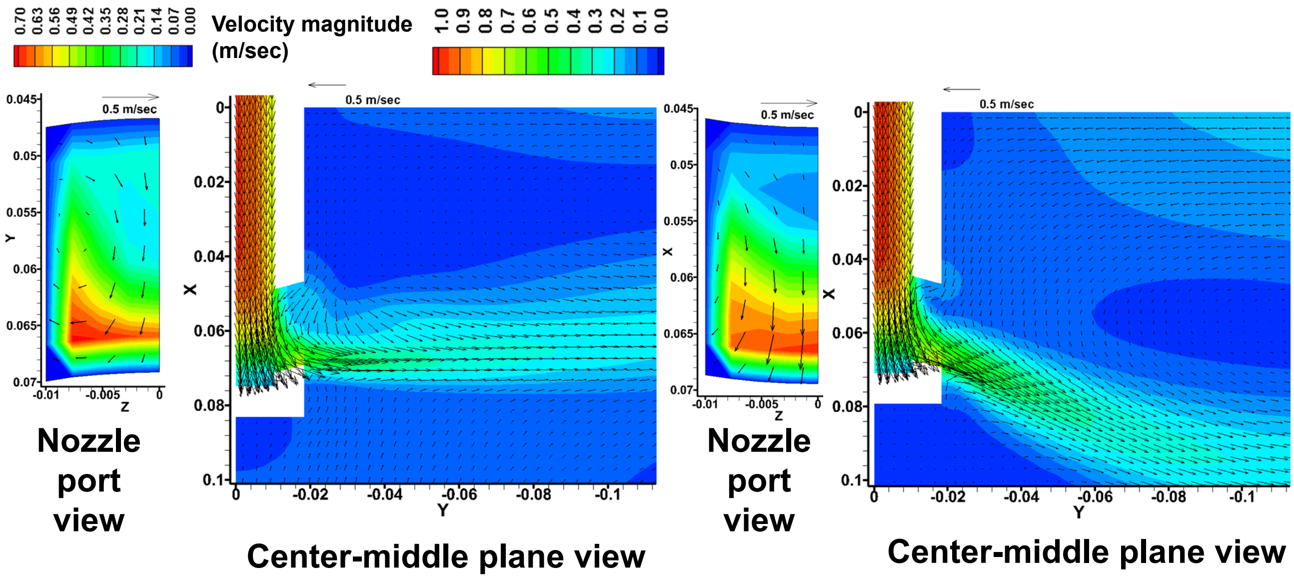
<Effect of number of cores on BW-core efficiency>



<Effect of distribution of nodes and cores on BW-core efficiency>

- Use of full 16 cores per 1 node for Fluent calculation on BW, has low efficiency: only 0.4 ~0.5 of lab computer computation using 1 core.
- For using same total cores (#48), BW calculation per 1 core shows much higher efficiency by increasing compute nodes.

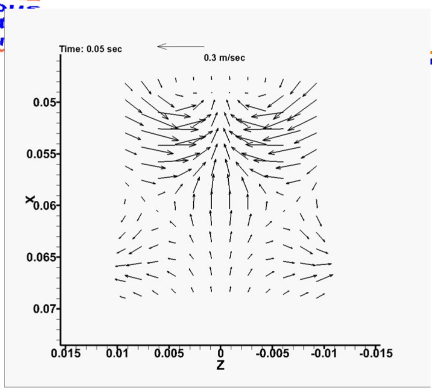
Time-averaged Jet Flow Patterns (Case W-LC)



Case W-LC. +15° (up) angle nozzle **Case W-LC. -15° (down) angle nozzle**

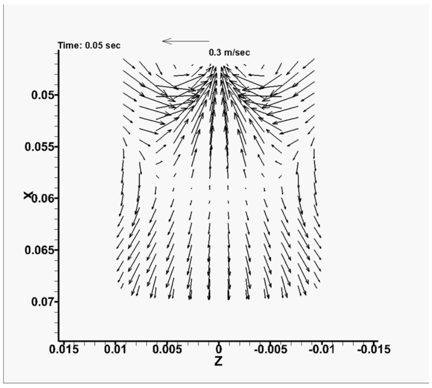
- Back flow from mold to nozzle port, get more with 15 ° (up) nozzle port
- Jet flow in the mold get deeper with -15 ° (down) nozzle port

Transient Swirl from Nozzle Port



Case W-BW. +15° (up) angle nozzle port

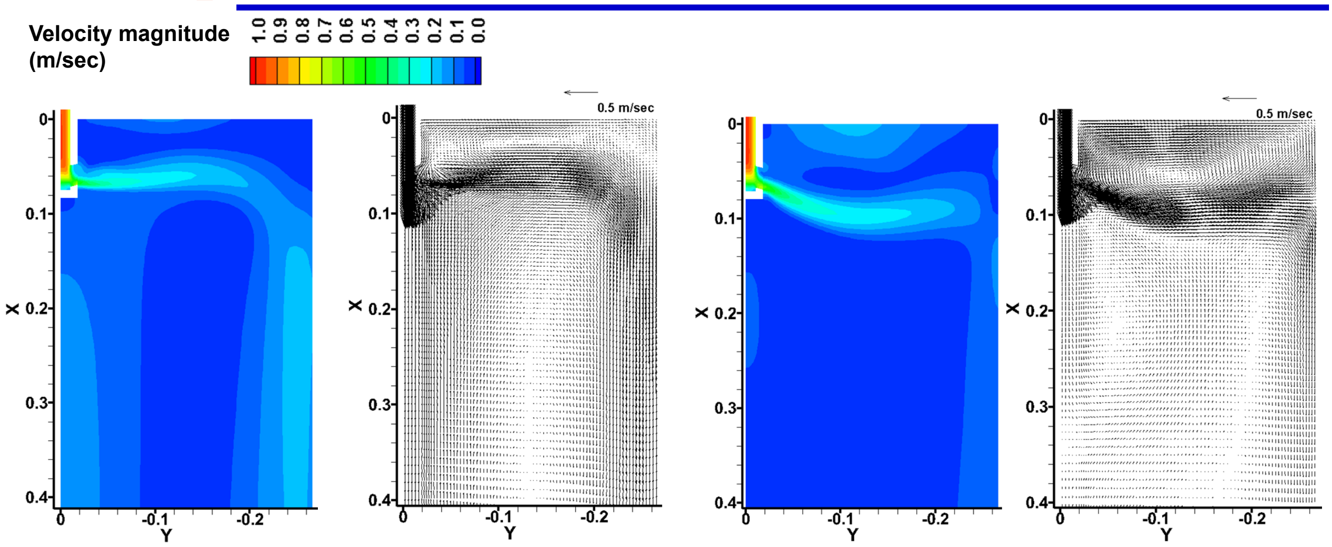
Case W. +15° (up) angle nozzle port



Case W-BW. -15° (down) angle nozzle port

Case W. -15° (down) angle nozzle port

Time-averaged Mold Flow Patterns (Case W-LC)

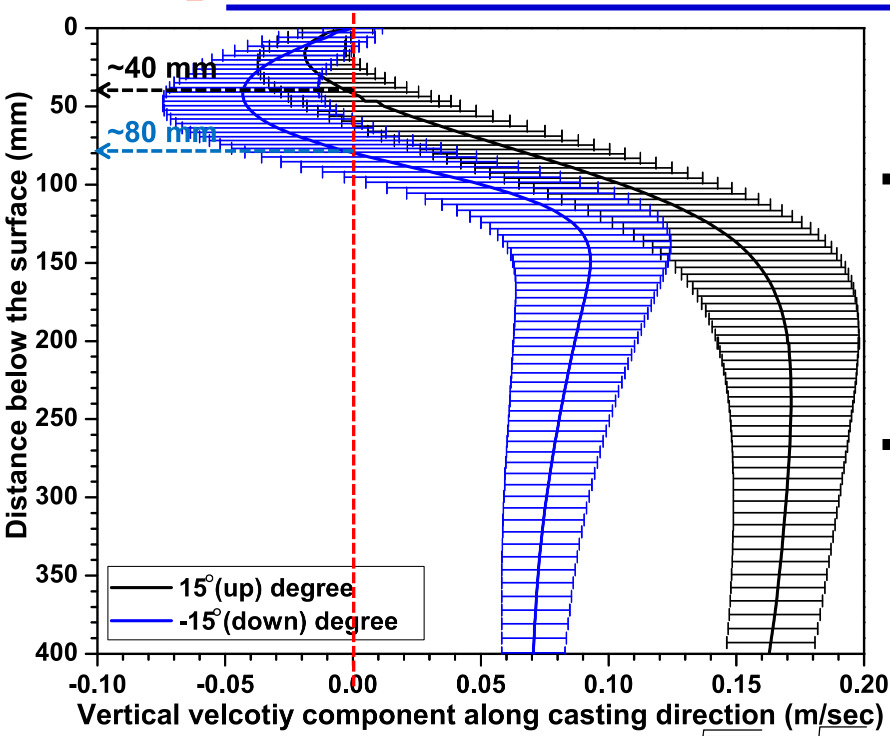


Case W-LC. +15° (up) angle nozzle

Case W-LC. -15° (down) angle nozzle

- With the nozzle port having +15 ° (up) angle, jet flow goes down deep into wide mold cavity: downward flow is predominant, this is very harmful to produce internal defects.
- Downward -15 ° degree nozzle port induces a classic double-roll pattern in wide mold.

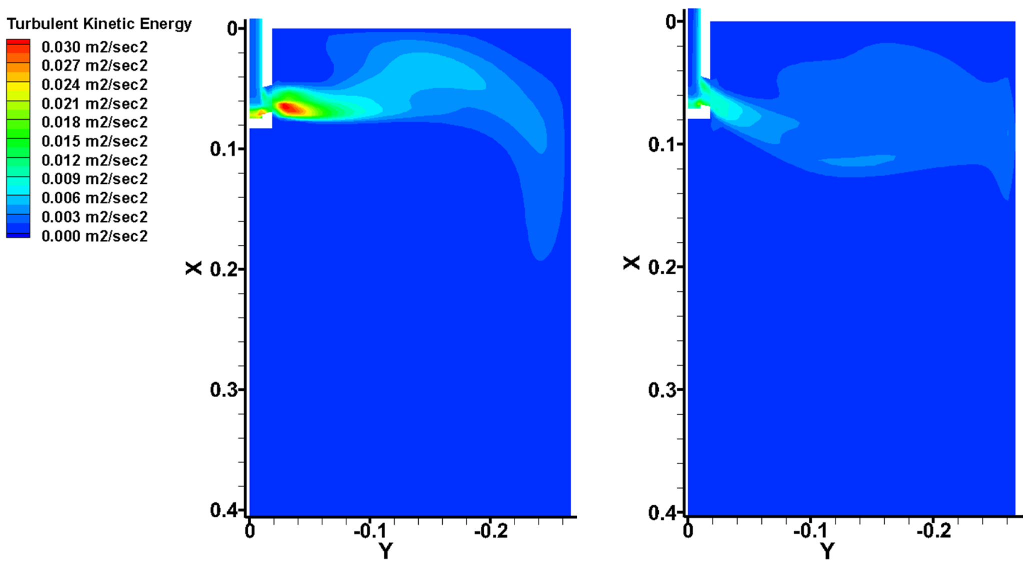
Vertical Velocity along NF (Case W-LC)



*Error bars: expected velocity fluctuations = $\sqrt{\overline{(u')^2}} = \sqrt{\frac{2}{3}k}$

- Jet flow impingement point on narrow face, is moved deeper into the mold cavity, by decreasing nozzle port angle.
- Upward angle of +15° causes strong downward flow along casting direction.

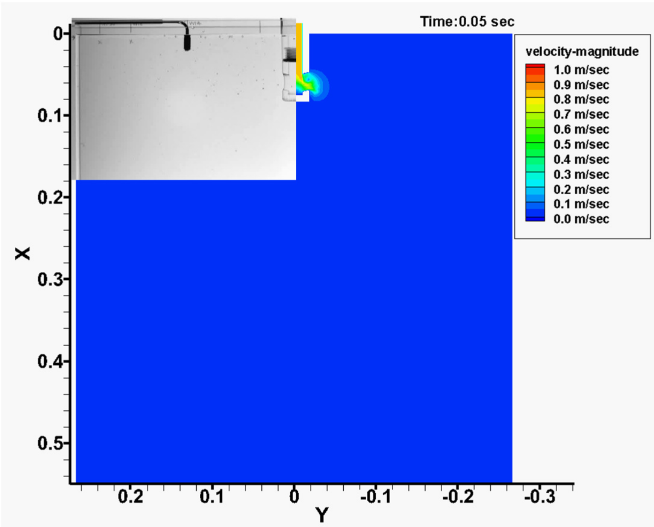
Turbulent Kinetic Energy in Mold (Case W-LC)

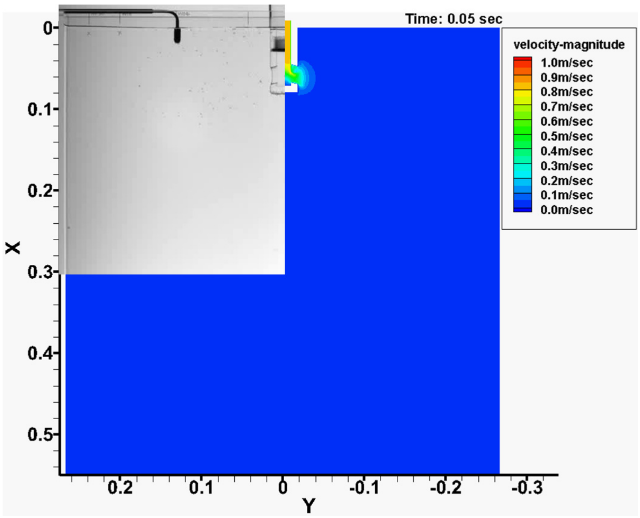


Case W-LC. +15° (up) angle nozzle **Case W-LC. -15° (down) angle nozzle**

- Jet wobbling is more severe with +15 (up) degree nozzle port, resulting in higher surface flow instability

Transient Mold Flow Patterns



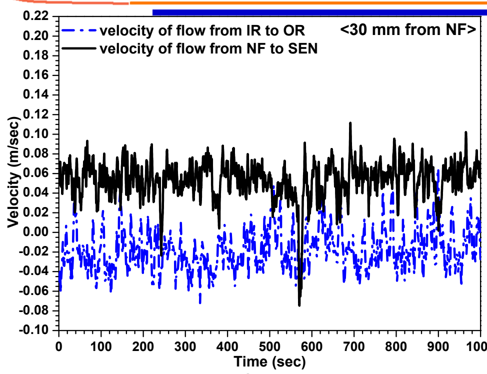


Predicted: Case W-BW. +15° (up) angle nozzle
Measured: Case W. +15° (up) angle nozzle

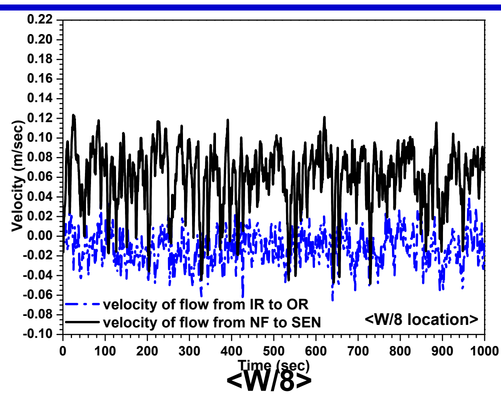
Predicted: Case W-BW. -15° (down) angle nozzle
Measured: Case W. -15° (down) angle nozzle

- From both measurements and predictions, the case of 15 (up) angle nozzle shows more variations of jet flow: Jet flow from the nozzle port with 15 (up) angle, induces more severe jet wobbling by producing more swirl flow?

Water Model Measurements: Surface Velocity with +15°(Up) Angle Port



<30 mm from NF>



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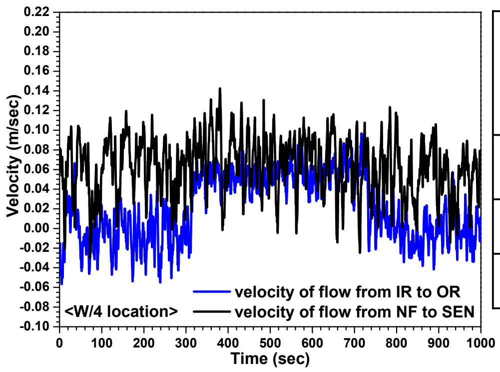

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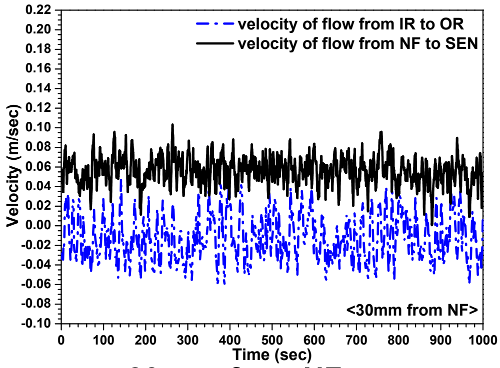
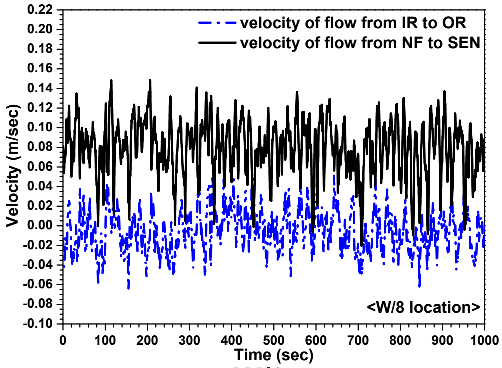
	Velocity of flow from IR to OR (m/s)		Velocity of flow From NF to SEN (m/s)	
	Average	Standard deviation	Average	Standard deviation
30 mm from NF	-0.0175	0.0215	0.0535	0.0189
W/8	-0.0118	0.0173	0.0595	0.0310
W/4	0.0218	0.0335	0.0628	0.0292

Water Model Measurements: Surface Velocity with +5° (Up) Angle Port



<30 mm from NF>



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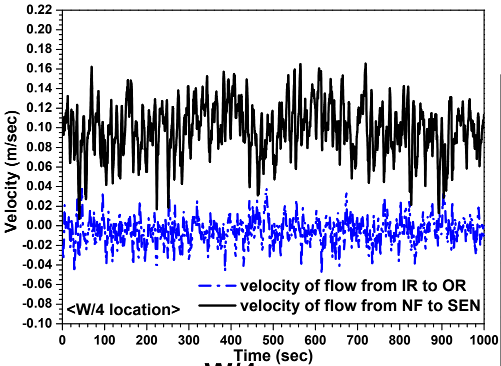

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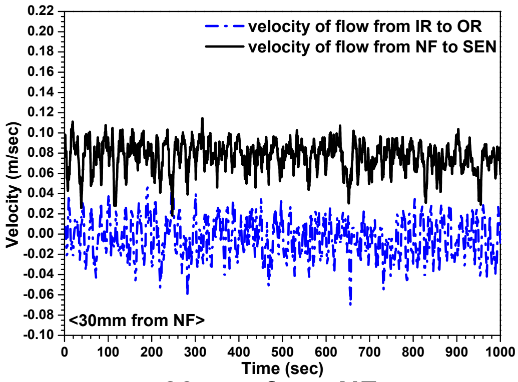
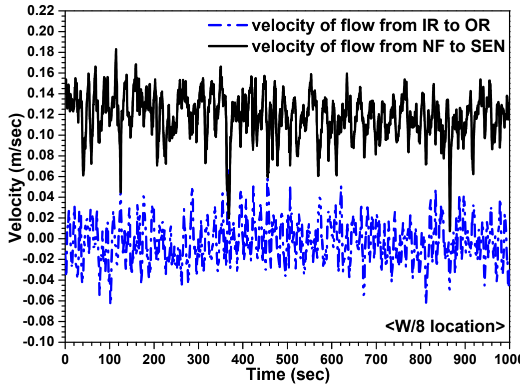
	Velocity of flow from IR to OR (m/s)		Velocity of flow From NF to SEN (m/s)	
	Average	Standard deviation	Average	Standard deviation
30 mm from NF	-0.0125	0.0226	0.0561	0.0141
W/8	-0.00473	0.0215	0.0795	0.0282
W/4	-0.00492	0.0134	0.0985	0.0265

Water Model Measurements: Surface Velocity with -15° (Down) Angle Port



<30 mm from NF>



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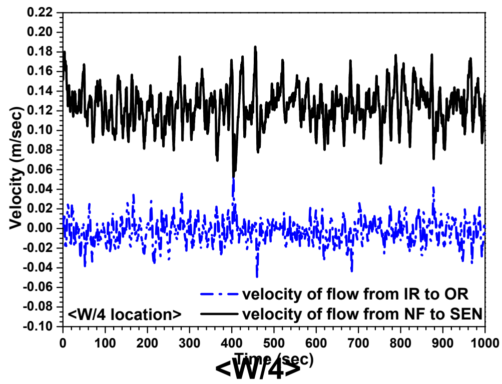

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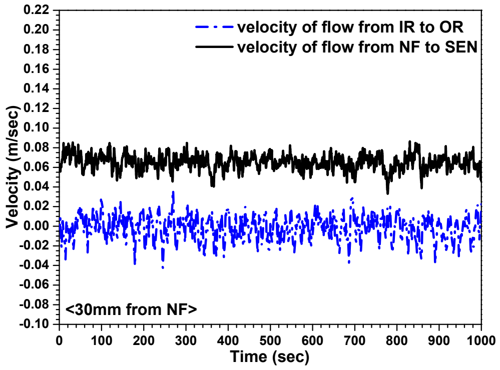
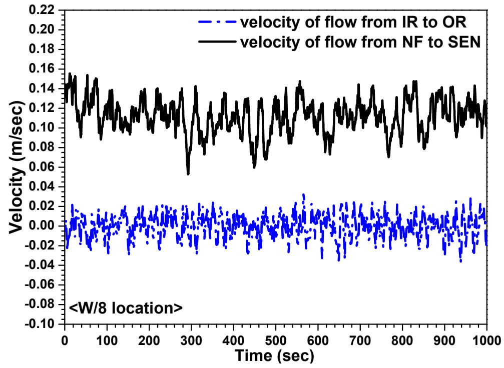
	Velocity of flow from IR to OR (m/s)		Velocity of flow From NF to SEN (m/s)	
	Average	Standard deviation	Average	Standard deviation
30 mm from NF	-0.00381	0.0190	0.0768	0.0144
W/8	-0.00266	0.0204	0.118	0.0213
W/4	-0.00278	0.0126	0.124	0.0199

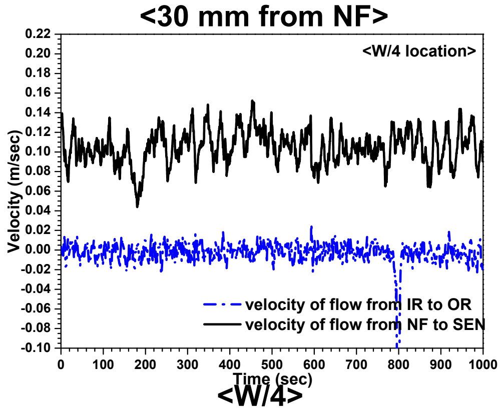
Water Model Measurements: Surface Velocity with -30° (Down) Angle Port



<30 mm from NF>



<W/8> (near NF)



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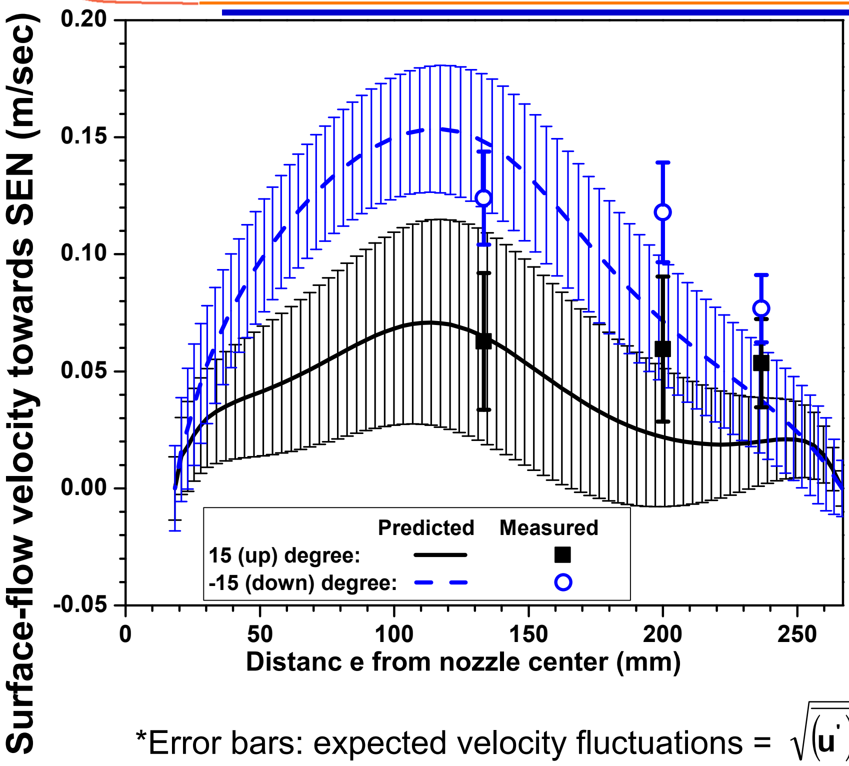
	Velocity of flow from IR to OR (m/s)		Velocity of flow From NF to SEN (m/s)	
	Average	Standard deviation	Average	Standard deviation
30 mm from NF	-0.00158	0.0124	0.0651	0.00762
W/8	0.0000297	0.0121	0.112	0.0173
W/4	-0.00305	0.0155	0.105	0.0172

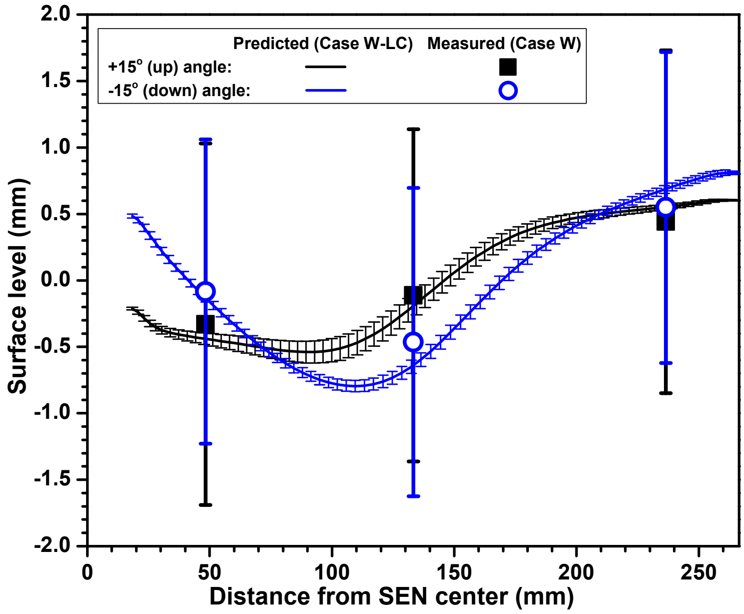
Model Validation (Results of Case W and Case W-LC) : Horizontal Surface Velocity



- RANS model using standard k-ε model agrees with water model measurements of surface velocity and its fluctuation

*Error bars: expected velocity fluctuations = $\sqrt{\overline{(u')^2}} = \sqrt{\frac{2}{3}k}$

Model Validation (Results of Case W and Case W-LC) : Surface Level



Average surface level profile (h_i):

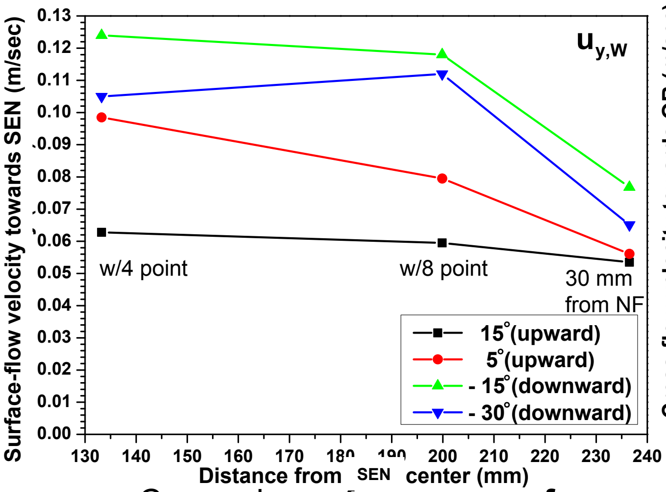
$$h_i = \frac{P_i - P_{AVG}}{\rho_w g}$$

Surface level fluctuation (Δh_i):

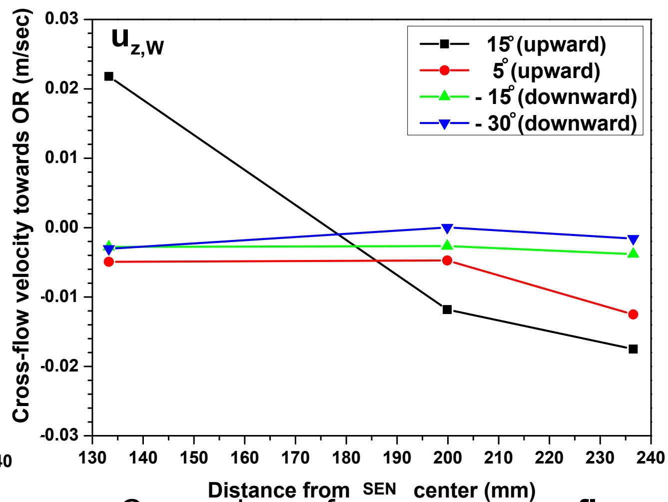
$$\Delta h_i = \frac{k}{g}$$

- RANS model using standard k-ε model agrees with water model measurements of average surface level profile
- Discrepancy of level fluctuation: Low resolution (0.5 mm) of level sensor is not sufficient to capture level fluctuations in water model mold.

Effect of Port Angle on Average of Velocity Components



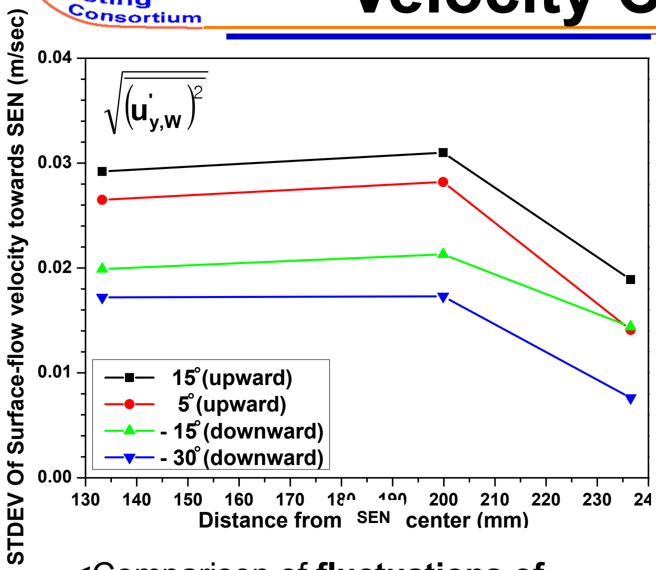
<Comparison of average **surface velocity component towards SEN**>



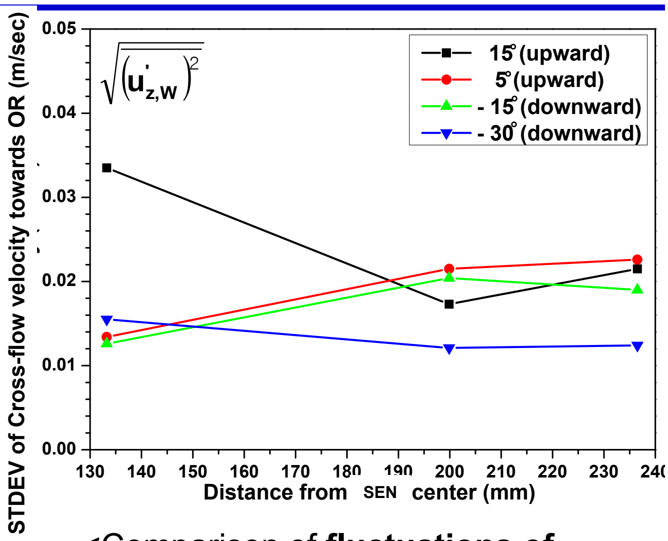
<Comparison of **average cross-flow velocity component towards OR**>

- The cases of downward port angle show higher surface velocity towards SEN, than upward angle cases
- -15° (down) angle port causes the highest surface velocity component towards SEN.
- Upward angle port produces more asymmetric flow between IR and OR than downward angle port.

Effect of Port Angle on Fluctuations of Velocity Components



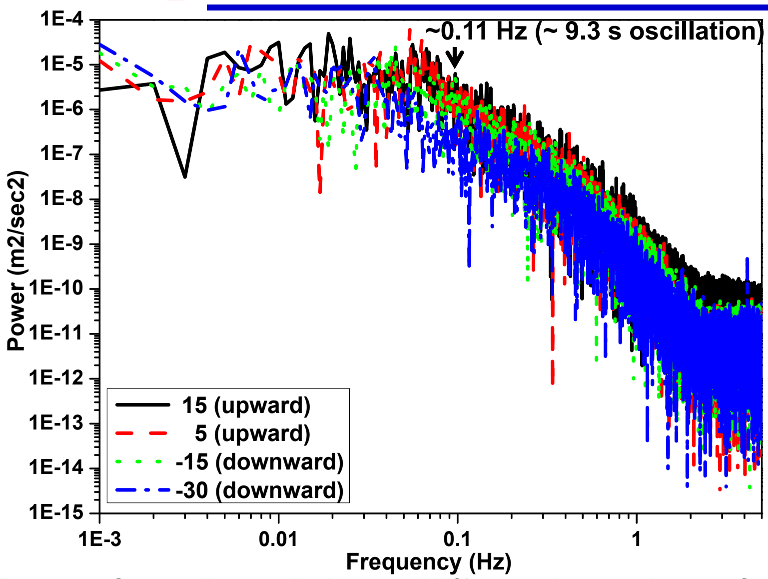
<Comparison of **fluctuations of velocity component towards SEN**>



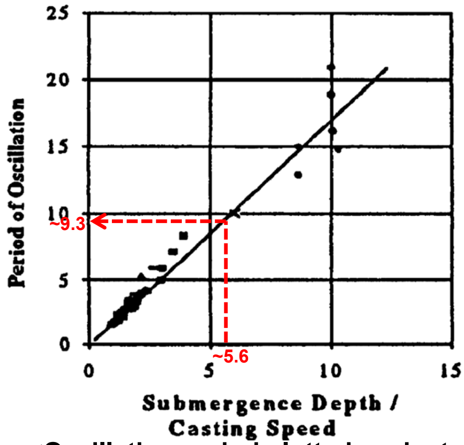
<Comparison of **fluctuations of velocity component towards OR**>

- Velocity fluctuations towards both SEN and OR, increase with increasing nozzle port angle

Power Spectrum Analysis of Transient Surface Velocity towards SEN of Water Model measurements



<Power of velocity variation on W/8 location at the surface>

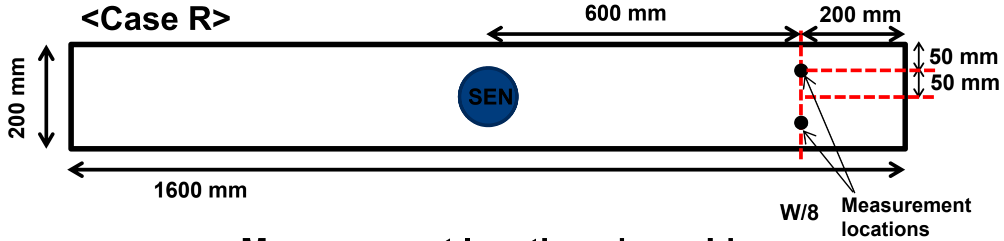


<Oscillation period plotted against ratios of submergence depths and casting speeds[*]>

*T.A. Honeyands and J. Herbertson: 127th ISIJ Meeting, Tokyo, Japan, March, 1994.

- Upward port angle induces stronger surface velocity variations.
- For the nozzle port with +15° (up) degree angle, the frequency of ~0.11 Hz, for asymmetric flow past the SEN predicted using Honeyands and Herbertson's relation, is found in the power spectrum

Nail Dipping Tests



<Measurement locations in mold>

<Solidified lump from nail dipping test>

Dipping test details

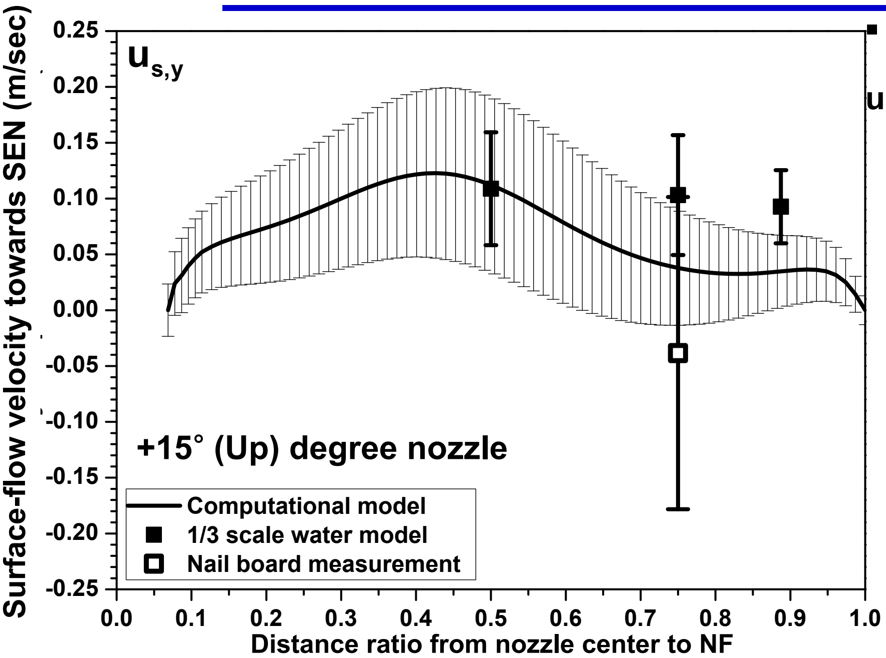
Total tests (for each IR and OR region)	5
interval of each test	1 minute
Dipping time	3 sec

Empirical equation for surface velocity magnitude[*]:

Surface velocity magnitude: $\mathbf{u_s(m/s) = 0.624 \cdot (\varphi_{lump}(mm))^{-0.696} \cdot (h_{lump}(mm))^{0.567}}$

* Liu et al., Proc. of TMS 2011,TMS, Warrendale, PA, USA

Comparison of Plant Measurements (Case R), 1/3 Scale Water Model Measurements (Case W), Computational Model (Case W-LC): All Scaled-Up of Surface Velocity for Real Caster



- **Scale up method:**

$$u_{s,R} = u_{s,W} \times \left(\frac{u_{in,R}}{u_{in,W}}\right)$$

Suggested by Singh, Thomas, and Vanka [*]

$$= u_{s,W} \times \frac{\left(\frac{u_{c,R} \times w_R \times t_R}{\pi (r_R)^2}\right)}{\left(\frac{u_{c,W} \times w_W \times t_W}{\pi (r_W)^2}\right)}$$

$$= u_{s,W} \times \boxed{\left(\frac{u_{c,R}}{u_{c,W}}\right)}$$

Froude number similarity

$$= u_{s,W} \times \boxed{\sqrt{\frac{L_R}{L_W}}}$$

$$\boxed{u_{s,R} = 1.73 \times u_{s,W}}$$

s: surface, in: nozzle inlet, r: nozzle inner radius
w: mold width, t: mold thickness,
L: process length scale

* Sigh et al., MMTB, Vol. 44B, 2013, p.1201-1221

- Limitation to understand surface flow in real wide-mold caster from water model measurement and computational modeling of water model: **Computational modeling for real caster case including steel shell and liquid mold flux layer is needed**

Summary:
Modeling and Measurements

- **1/3 scale water model experiments, plant measurements, and computational modeling** using both lab computer and Blue Waters supercomputer, were performed to investigate effect of nozzle port angle on nozzle and mold flow, for reducing surface defects in wide slab.
- Reynolds-Averaged Navier-Stokes (**RANS**) **model** using **standard k-ε model on lab computer** and **Large Eddy Simulation (LES) on Blue Waters supercomputer,** were used to quantify time-averaged and - dependent flow in 1/3 scale water model
- **RANS model** shows a very good quantitative match with **average surface velocity profile** across 1/3 scale water model.
- **LES model** can capture **transient nozzle swirl** and **jet wobbling**, which is important transient flow phenomena to cause surface instability, related to surface defect formation with nozzle port angle effect.
- Water model surface velocities near narrow face exceed those in real wide-mold caster.
- **Transient flow modeling including steel shell and liquid mold flux layer, is likely needed** to understand surface flow variations (especially, near NF) in wide mold of real caster

Summary:
Effect of Nozzle Port Angle & Suggestion

- Jet flow from **+15° (up) nozzle port** shows more **severe wobbling** than +5°(up), -15°(down), -30°(down) ports; this jet impinges first on top surface causing surface instability (the highest surface velocity variations even though it has the lowest surface velocity).
- **Higher surface velocity fluctuations not always caused by faster surface flow: surface instability depends on casting conditions**
- **Maximum average surface velocity** is produced by port angle of **-15° (down)**.
  - Deeper port angle (-30° (down)) has slower surface velocity.
  - Shallower port angle (+5° (up) and +15° (up) degree) has slower surface velocity.
- **Maximum surface velocity when jet impinges on NF at upward angle: Surface velocity slower if jet first impinges on NF at downward angle or near top surface or corner**
- **Up-angled nozzle with non-optimized SEN depth** could be detrimental in causing both **severe surface instability (surface defects)** and **abnormal downward flow (internal defects)** deep into mold cavity.
- Worst flow pattern (from +15° in this work) is unstable between single and double-roll: pressure sucks jet up to impinge top surface; or down to impinge on NF; wobbling between causes instability and defects)
- Deeper submergence is suggested for up-angled nozzle in this caster system to enable jet flow-hit to impinge first on NF
- High-frequency low-amplitude turbulence is optimal to get mixing, heat transfer to meniscus without surface instability:
  Avoid High-power lower-frequency oscillations with large spatial variations.

Acknowledgments

- Continuous Casting Consortium Members (ABB, AK Steel, ArcelorMittal, Baosteel, JFE Steel Corp., Magnesita Refractories, Nippon Steel and Sumitomo Metal Corp., Nucor Steel, Postech/ Posco, SSAB, ANSYS/ Fluent)
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