MechSE

ANNUAL REPORT 2011

UIUC, August 18, 2011

Transient Turbulent Flow Simulation with Water Model Validation and Application to Slide Gate Dithering

R. Liu[1], B. Forman[2], H. Yin[2] and B.G. Thomas[1]

[1]*Department of Mechanical Science and Engineering*
University of Illinois at Urbana-Champaign

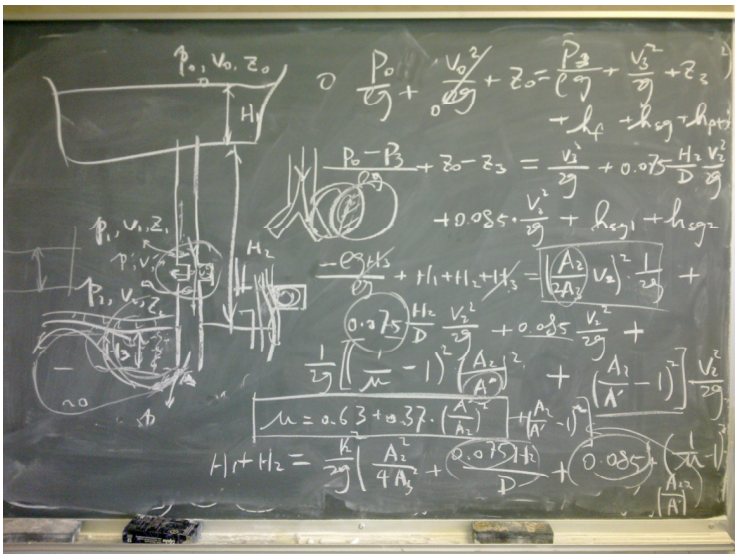
[2]*ArcelorMittal Global R&D*
at East Chicago

Objectives

1) To develop flow rate vs. slide-gate opening curves
2) CFD model evaluation/validation
   - To explore the best way (choice of turb. models, adv. schemes e.g.), to perform CFD simulations in slide-gate systems
   - To test the effect of meshes on the final results (tetra- vs. hexa-cell meshes)
3) To study transient flow effects, such as slide-gate dithering on the flow patterns in SEN and mold

Part 1

Development of Flow Rate vs. Slide Gate Opening Curves



Model to Relate Flow Rate & Slide Gate Position

- **Needed for:**
  - **Water model simulation, to determine/check slide-gate position for computational model geometry based on measured flow rate**
  - **To determine the transient flow rate for the slide-gate dithering study, based on measured gate position vs time**
  - **In future, to study or predict nozzle clogging conditions during real casting process, knowing both flow rate and gate position**

Analysis of Bernoulli's Equation

$$\frac{p_0}{\rho g}+\frac{v_0^2}{2g}+z_0=\frac{p_3}{\rho g}+\frac{v_3^2}{2g}+z_3+h_{port}+h_f+h_{sg}$$

0

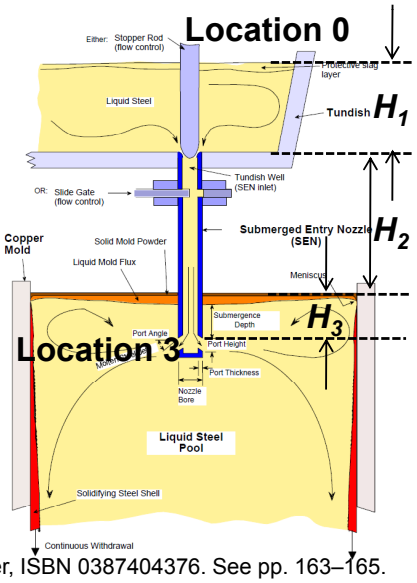
$$\frac{p_0-p_3}{\rho g}+z_0-z_3=\frac{v_3^2}{2g}+\sum h \rightarrow h_{port}+h_f+h_{sg}$$

$$-H_3 \qquad H_1+H_2+H_3 \qquad \frac{v_{SEN}^2}{2g}\left(\frac{A_{SEN}}{A_{port}}-1\right)^2 \qquad f\frac{L_{SEN}}{D_{SEN}}\frac{v_{SEN}^2}{2g}$$

$$p_0=1.01\times10^5\,Pa$$

$$p_3=\rho g H_3+p_0$$

$$z_0-z_3=H_1+H_2+H_3$$



$$h_{sg}=\left(\left(\frac{1}{\mu}-1\right)^2\left(\frac{A_{SEN}}{A_{GAP}}\right)^2+\left(\frac{A_{SG}}{A_{GAP}}-\frac{A_{GAP}}{A_{SG}}\right)^2\left(\frac{A_{SEN}}{A_{SG}}\right)^2\right)\frac{v_{SEN}^2}{2g}$$

$$\mu=\frac{A_{vc}}{A_{SG}}=\begin{cases}0.63+0.37\left(\frac{A_{GAP}}{A_{SG}}\right)^3 & \text{Model 1}^{[1]}\\ 0.5864+0.2762\left(\frac{A_{GAP}}{A_{SG}}\right)-0.4807\left(\frac{A_{GAP}}{A_{SG}}\right)^2+0.618\left(\frac{A_{GAP}}{A_{SG}}\right)^3 & \text{Model 2}^{[2]}\\ 0.64 & \text{Model 3}^{[3]}\end{cases}$$

Ref:

[1] Oertel, Herbert; Prandtl, Ludwig, et.al, Prandtl's Essentials of Fluid Mechanics, Springer, ISBN 0387404376. See pp. 163–165.
[2] Evangelista Torricelli, 1643; [3] http://en.wikipedia.org/wiki/Vena_contracta

Gate-Position-based Model (considering gas addition)

- **Gate-position-based model 1:**

$$Q_{SEN}=A_{eff}\sqrt{\frac{2g\left(H_1+H_2\right)}{\left(\frac{A_{SEN}}{A_{port}}-1\right)^2+f\frac{L_{SEN}}{D_{SEN}}+\left(\frac{1}{\mu}-1\right)^2\left(\frac{A_{SEN}}{A_{GAP}}\right)^2+\left(\frac{A_{SG}}{A_{GAP}}-\frac{A_{GAP}}{A_{SG}}\right)^2\left(\frac{A_{SEN}}{A_{SG}}\right)^2+\left(\frac{A_{SEN}}{2A_{port}}\right)^2}}$$

where $\mu=0.63+0.37\left(\frac{A_{GAP}}{A_{SG}}\right)^3$

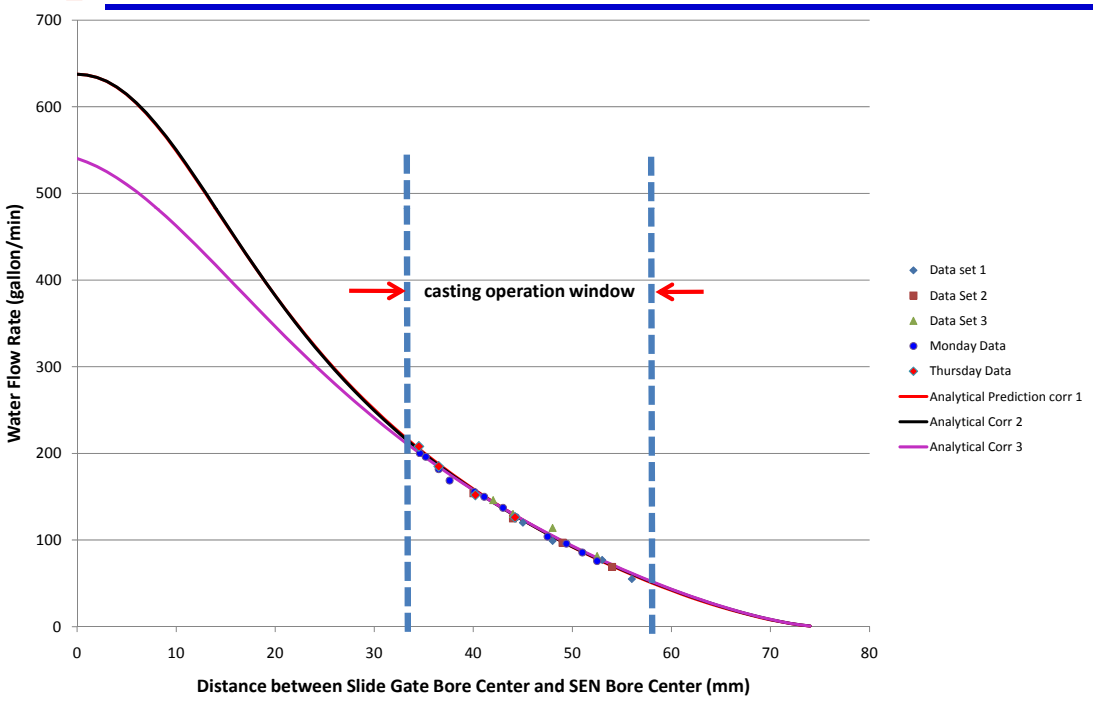
$$A_{eff}=\begin{cases}A_{SEN} & \text{single phase flow}\\ \frac{Q_{liquid}}{Q_{gas}+Q_{liquid}}A_{SEN} & \text{two phase flow}\end{cases}$$

For continuous caster, an extra term should be added to account for pressure drop due to clogging:

$$Q_{SEN}=A_{eff}\sqrt{\frac{2g\left(H_1+H_2\right)}{\left(\frac{A_{SEN}}{A_{port}}-1\right)^2+f\frac{L_{SEN}}{D_{SEN}}+\left(\frac{1}{\mu}-1\right)^2\left(\frac{A_{SEN}}{A_{GAP}}\right)^2+\left(\frac{A_{SG}}{A_{GAP}}-\frac{A_{GAP}}{A_{SG}}\right)^2\left(\frac{A_{SEN}}{A_{SG}}\right)^2+\left(\frac{A_{SEN}}{2A_{port}}\right)^2+C}}$$

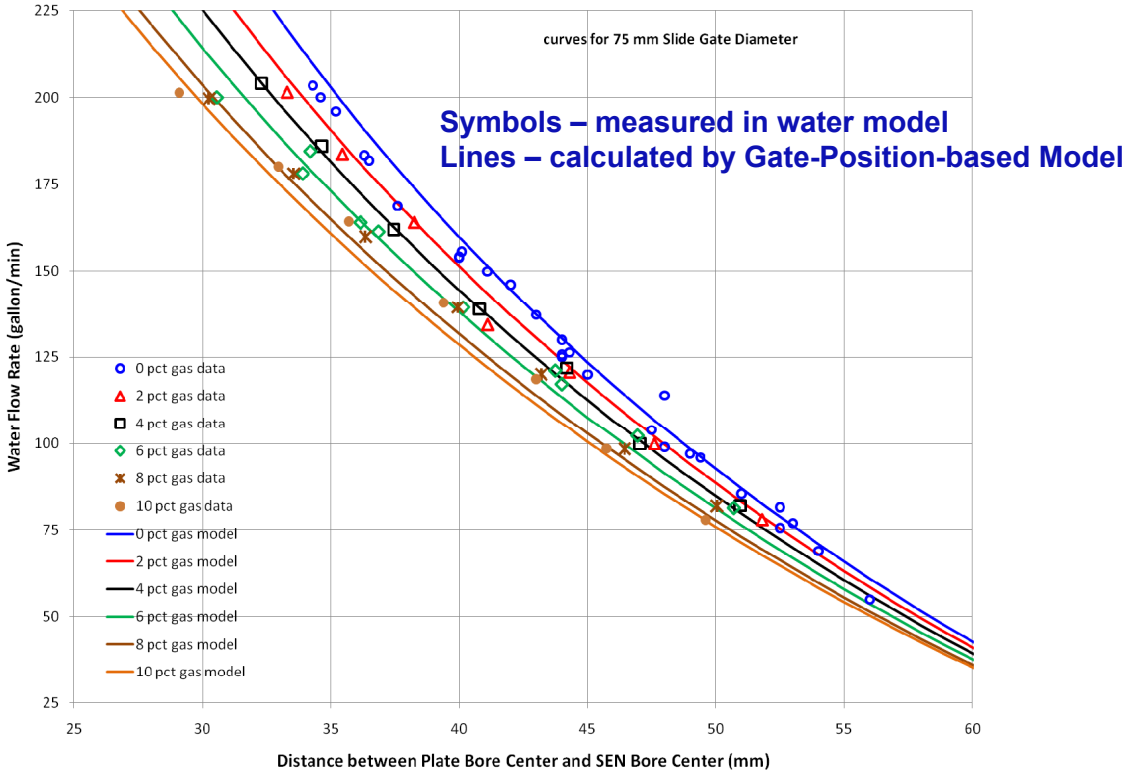
In current study, *C=0* is assumed (no clogging).

Curves from Different Models



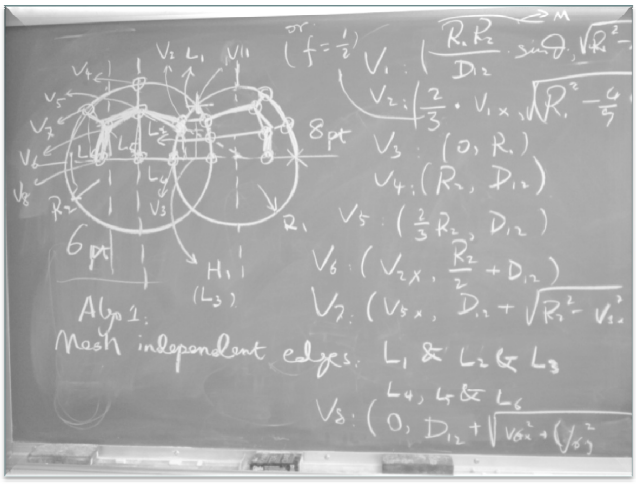
- **Deviation found as slide open gate opening increases, but outside the casting operation window, thus all three correlations are equivalent**

Gate opening / Flow-rate Curves for Different Gas Fractions



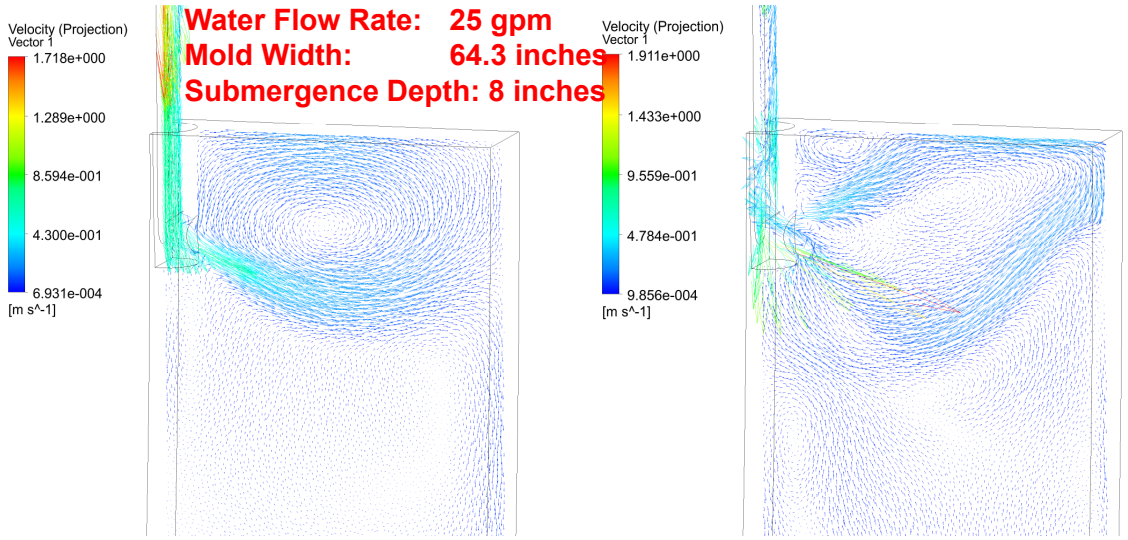
Part 2

Computational Model Evaluation via Single-Phase Water Model Experiments



Model Validation – Case 1

- Flow Pattern in center plane between broad faces



SST model, 1st order upwind scheme

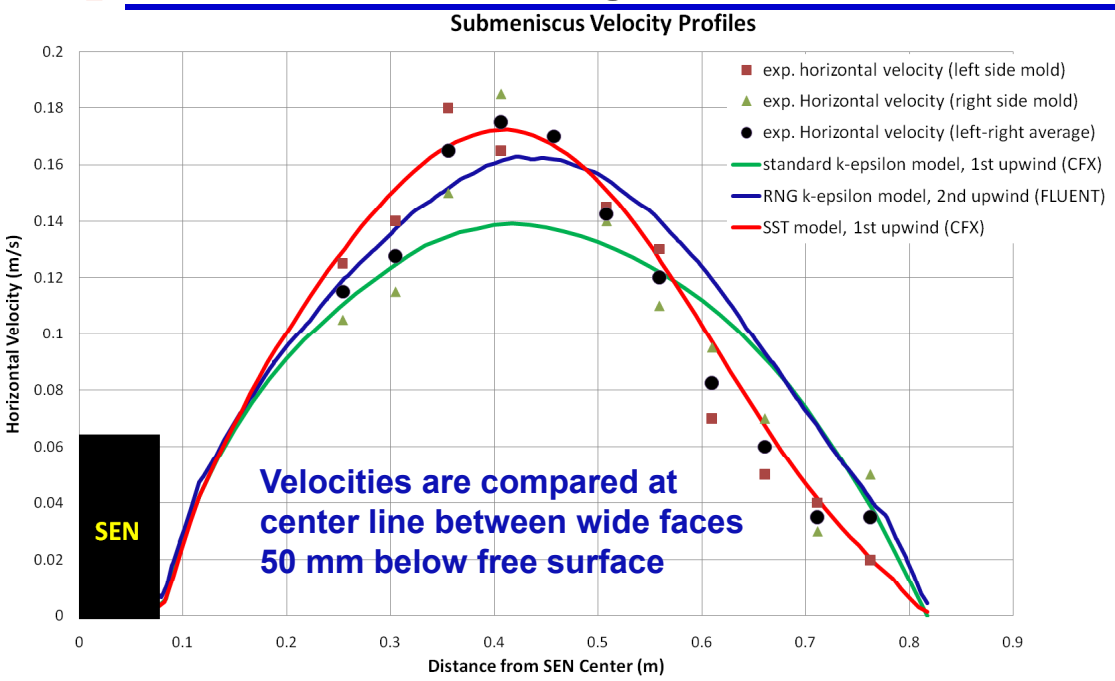
Physical result

SST model, high resolution scheme

Unphysical result

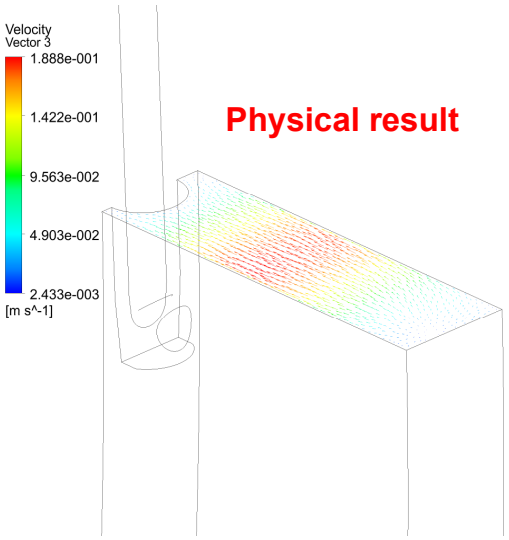
-- simulations using CFX

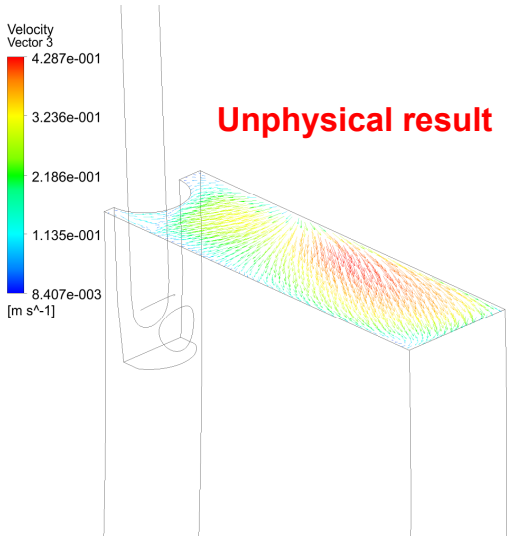
Comparison of Horizontal Velocity Profiles



- **Shear Stress Transport (SST) model gives best match with experiment data in this case, where the port exit jet has a strong swirling. SKE and RNG models are also reasonable.**

Meniscus Velocity Distribution



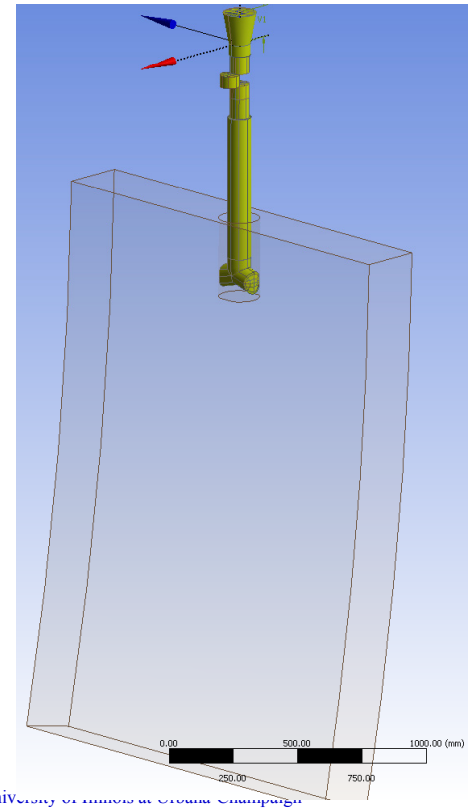


SST model, 1st order upwind scheme

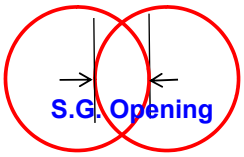
SST model, high resolution scheme

Either k-epsilon model or SST model will lead to unphysical flow pattern in the mold (as shown on the right) without using 1st order upwind scheme

Model Validation – Case 2



Mold Width: 64.3 inches
Mold Thickness: 9.25 inches
SEN Submergence Depth: 8 inches
Slide Gate Opening: 31 mm
(defined as below)

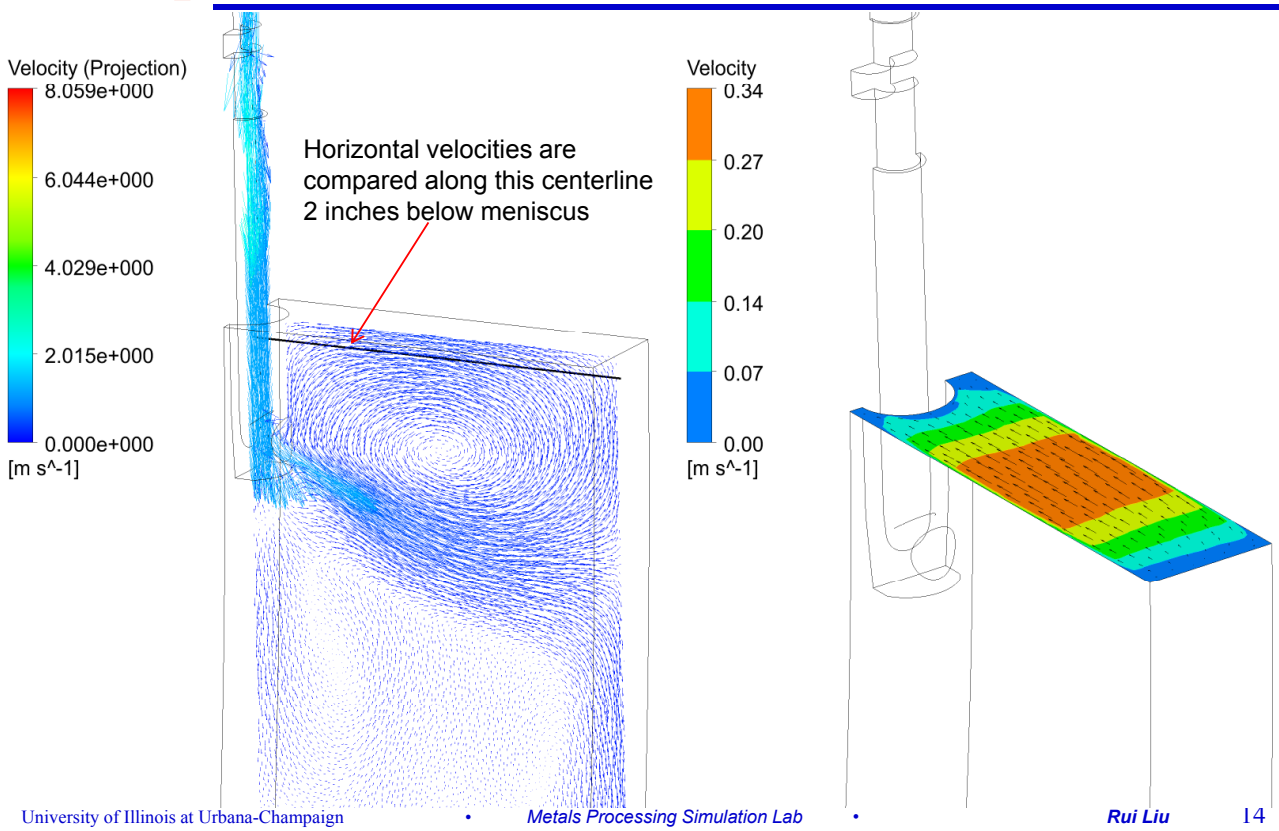


S.G. opening =
D_{plate} – Center Distance

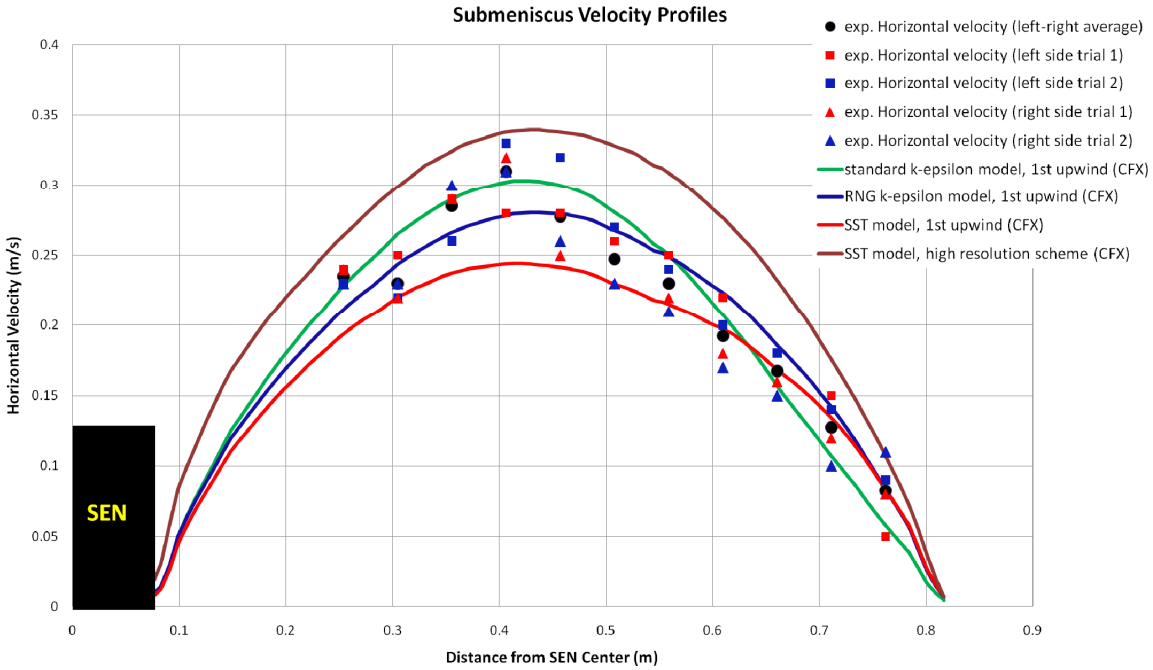
Casting Speed: 45 ipm
(125 gallon/min)
SEN inner bore diameter: 92 mm
Plate Diameter: 75 mm

--Total 1.1 million Tetra cells
-- Half mold was used as computational domain

Flow Pattern at Center Plane and Meniscus



Comparison of Horizontal Velocity Profiles



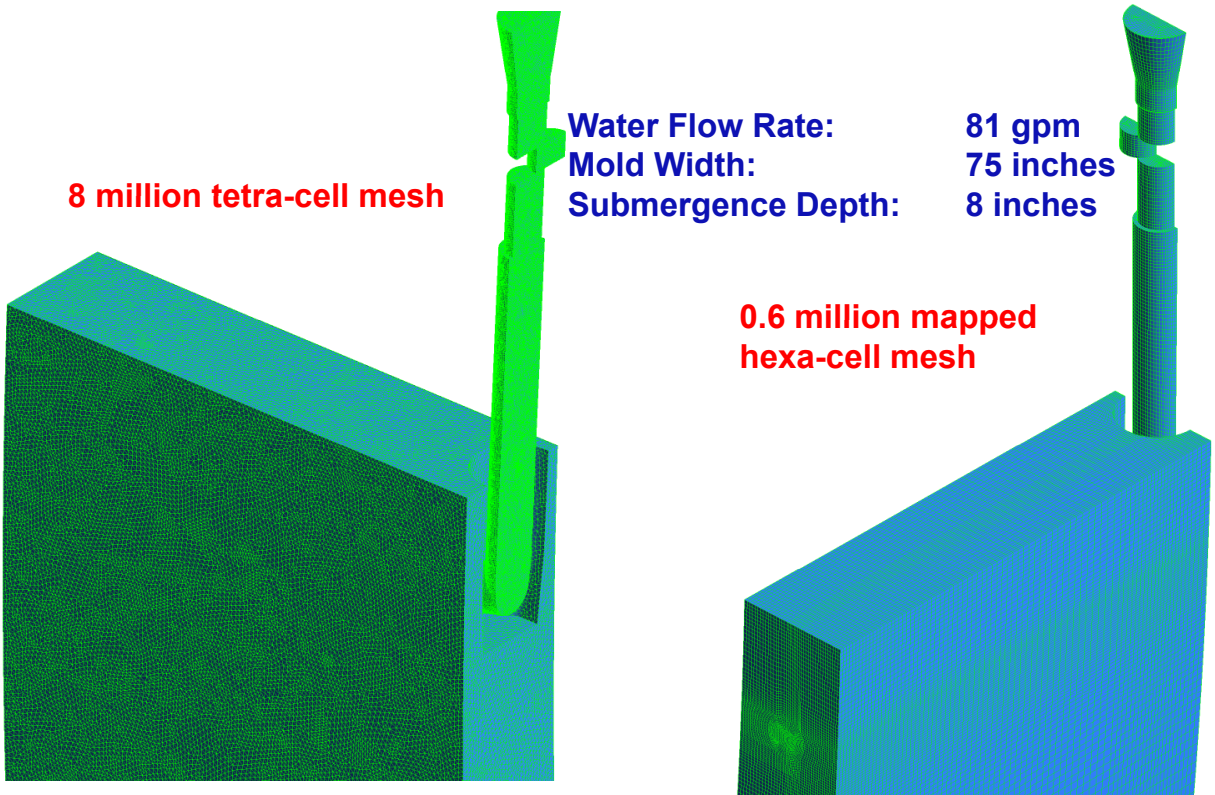
The standard k-epsilon model (and 1st order upwind scheme) is matching best with the general trend of the measured data.

Model Validation –Case 3

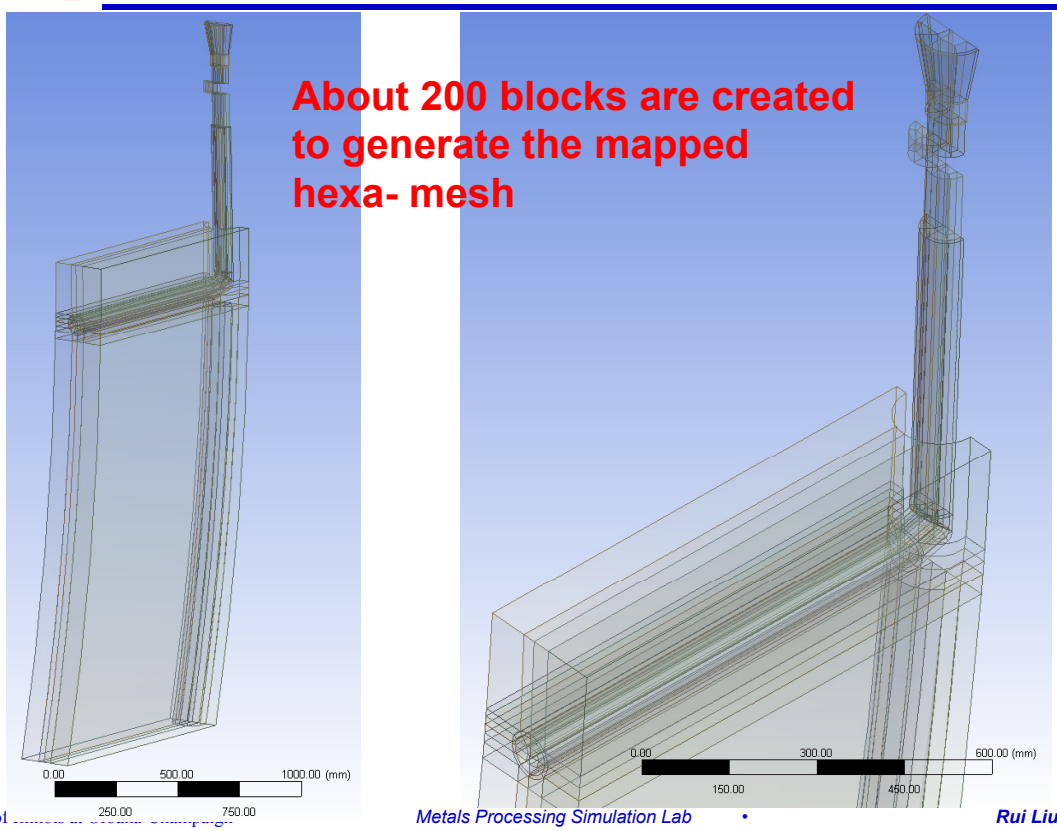
8 million tetra-cell mesh

Water Flow Rate: 81 gpm
Mold Width: 75 inches
Submergence Depth: 8 inches

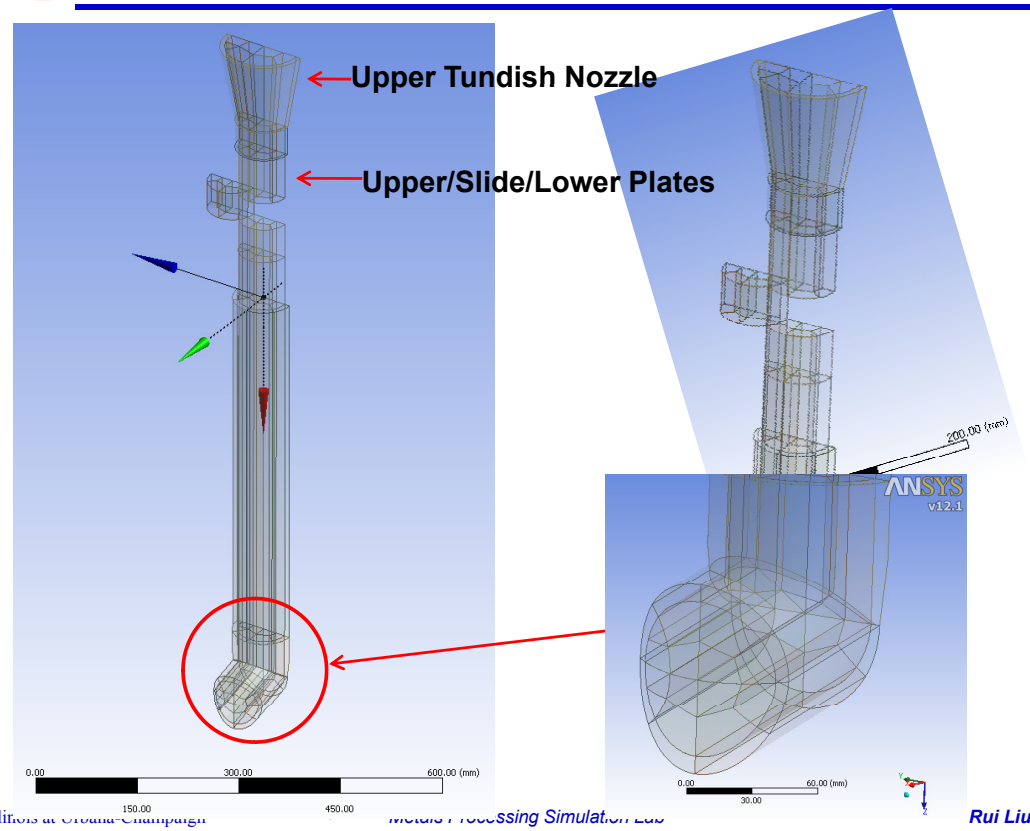
0.6 million mapped hexa-cell mesh



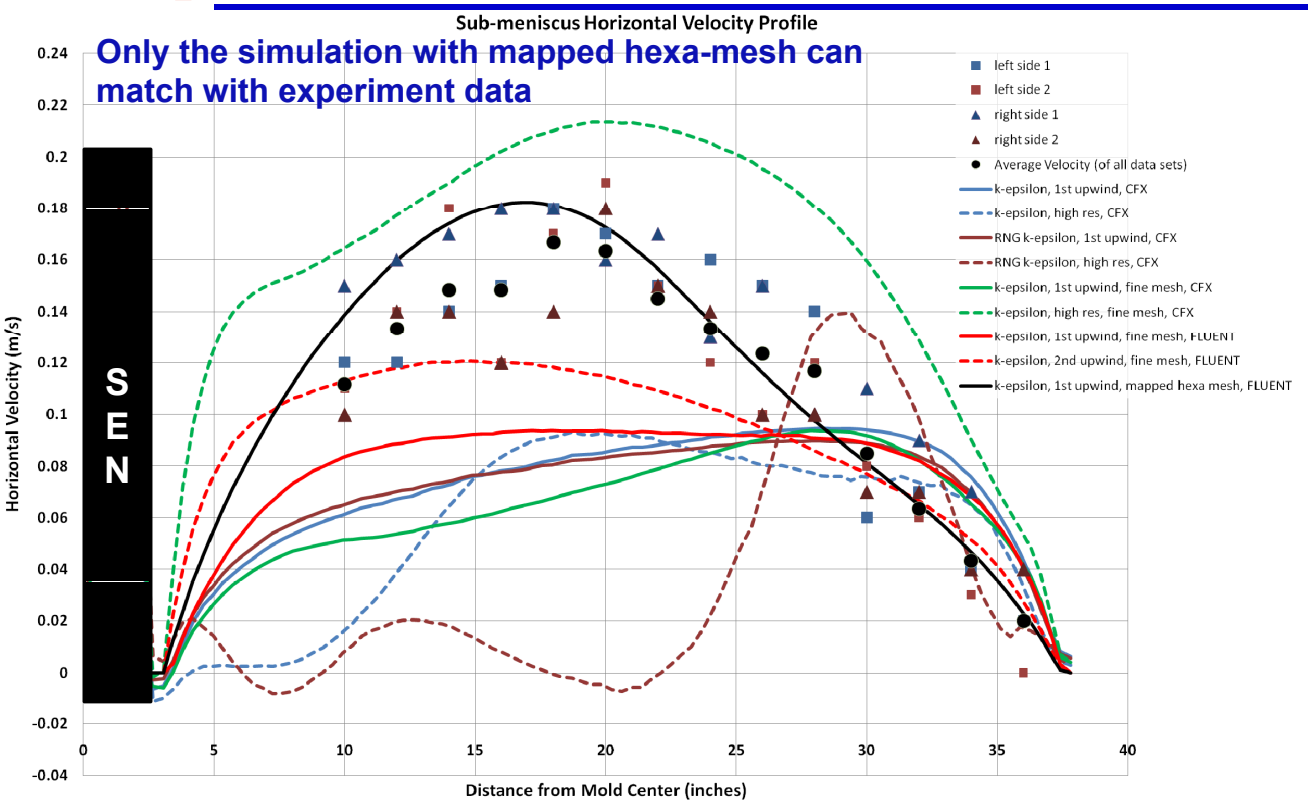
Blocks to Create Mapped Hexahedral Cells



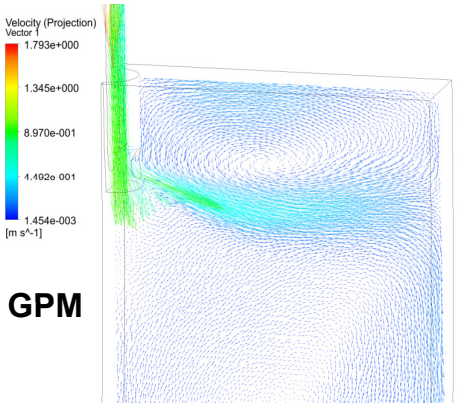
Blocks for Nozzle and SEN



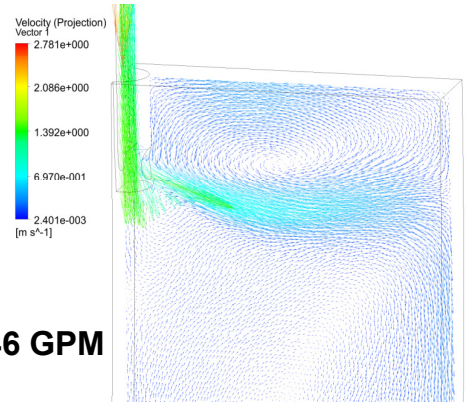
Comparison of Velocity Profiles



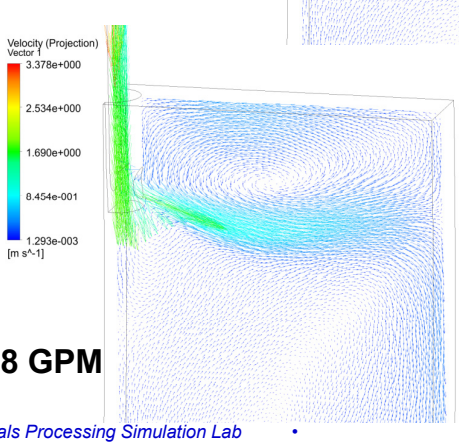
Flow Patterns in the Mold --75-inch mold width case



81 GPM



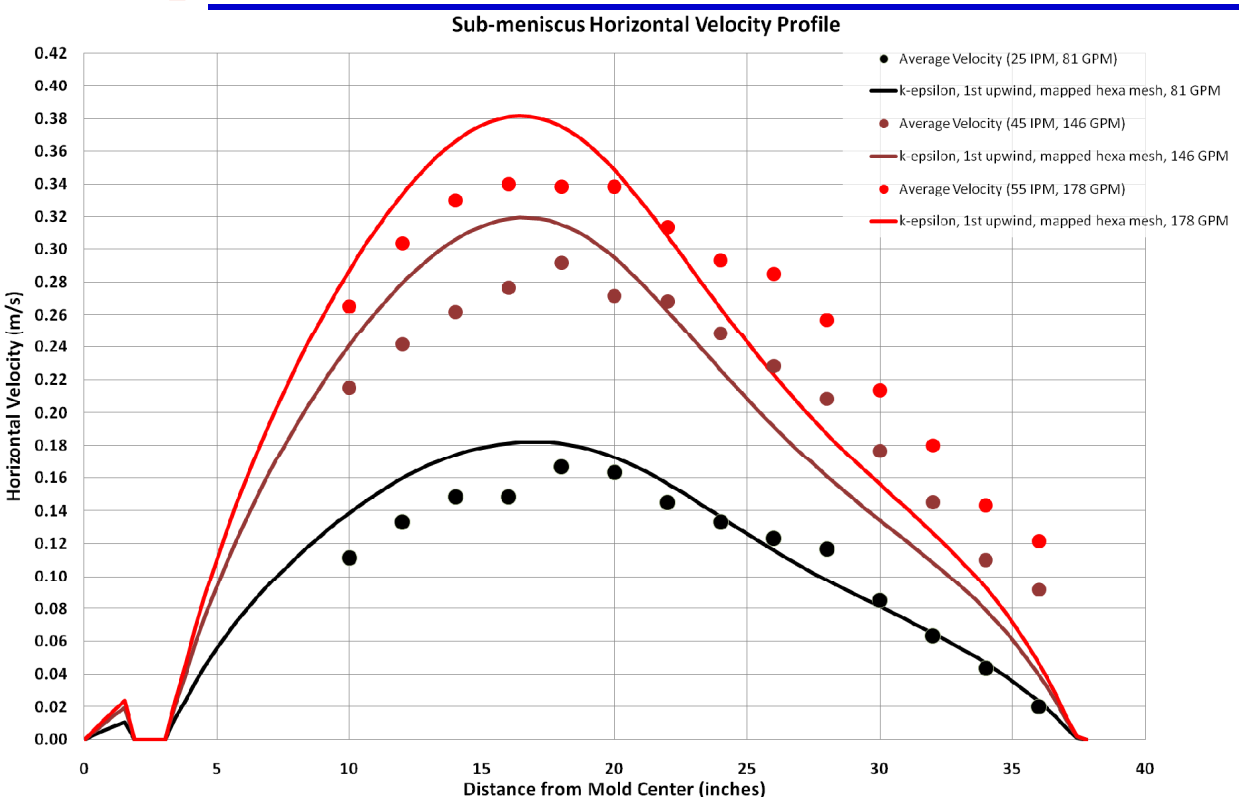
146 GPM



178 GPM

1. Flow patterns with different water flow rate are similar with different velocity scales;
2. Double roll flow pattern is observed in all cases.

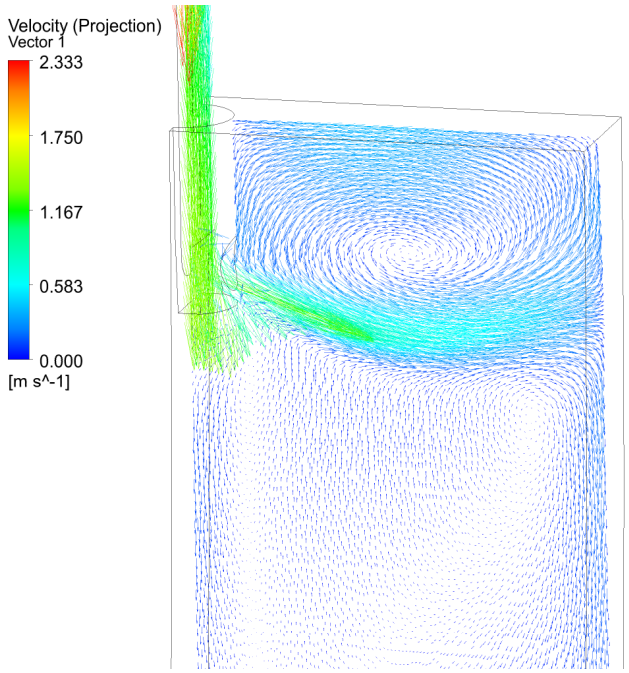
Comparison of Horizontal Velocity Profiles –75 inch Mold

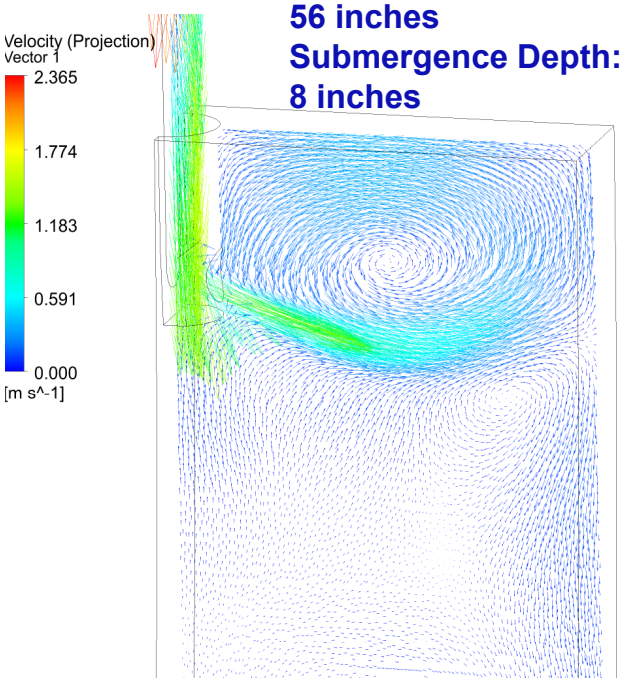


Model Validation –Case 4

- k-e vs. RSM

Mold Width: 56 inches
Submergence Depth: 8 inches

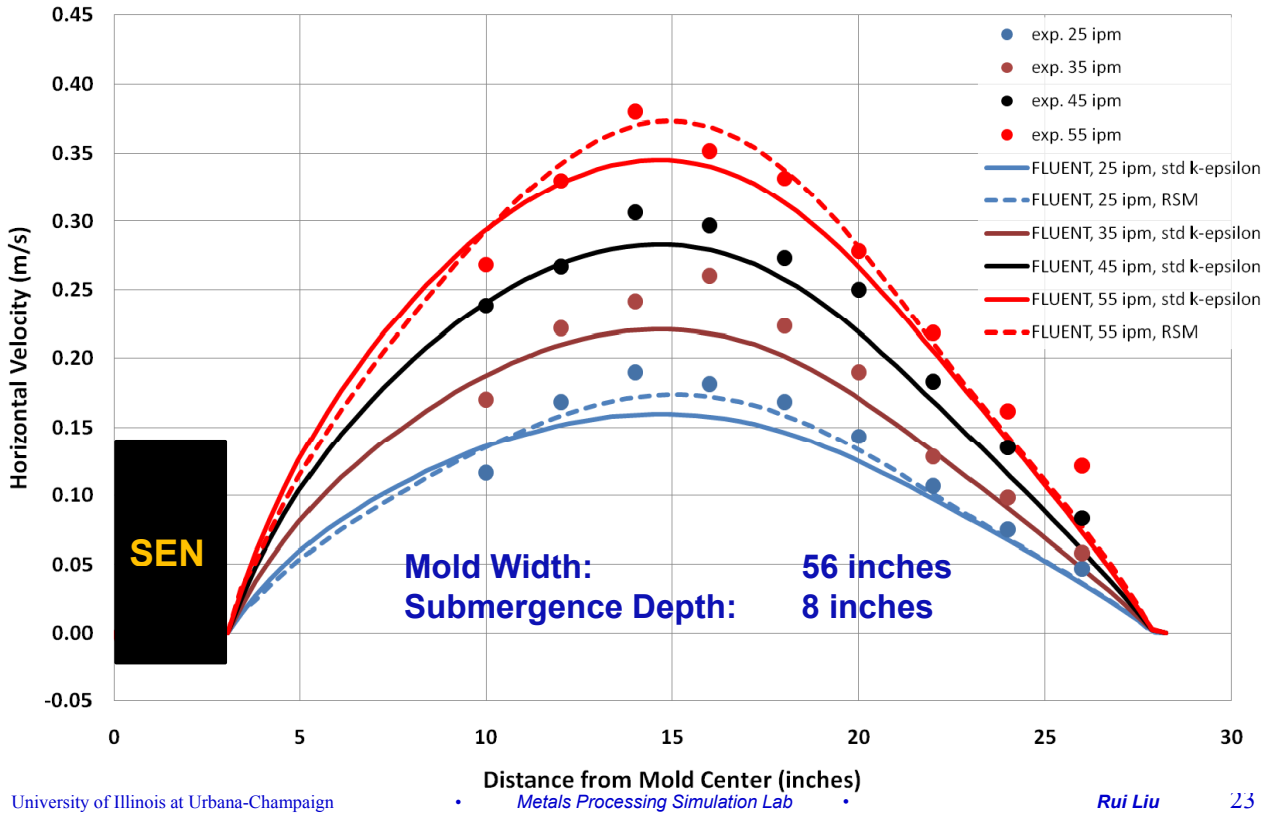




55 ipm, std k-epsilon model

55 ipm, RSM model

Comparison of Horizontal Velocity Profiles –56 inch Mold



Conclusions –Part 2

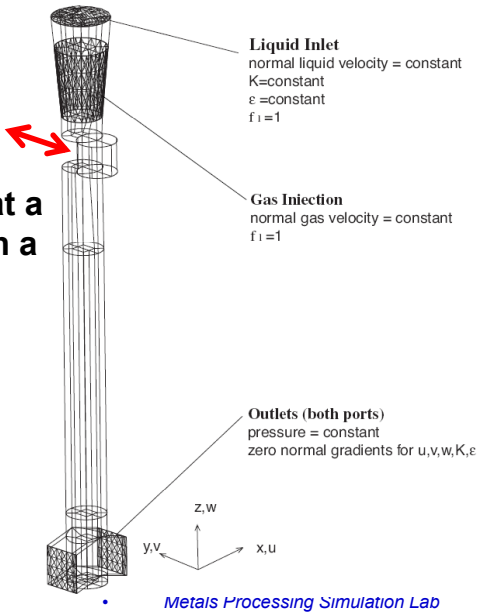
- Computational models are validated using the sub-meniscus velocity measurements performed in the full-scale water model in AM at East Chicago.
- **Numerical experiments show that:**
  - **Standard k-epsilon model is the most robust turbulence model to use;**
  - **Mapped hexa-cell meshes have better accuracy and stability in computation comparing with tetra-cell meshes**
  - **1st order upwind scheme matches best with experiment data, the reason might be due to the compensation of lack of turb. Kinetic energy production at free shear layer by the RANS model via numerical diffusion.**

Part 3

Transient Flow Simulation of Slide Gate Dithering

Slide Gate Dithering:

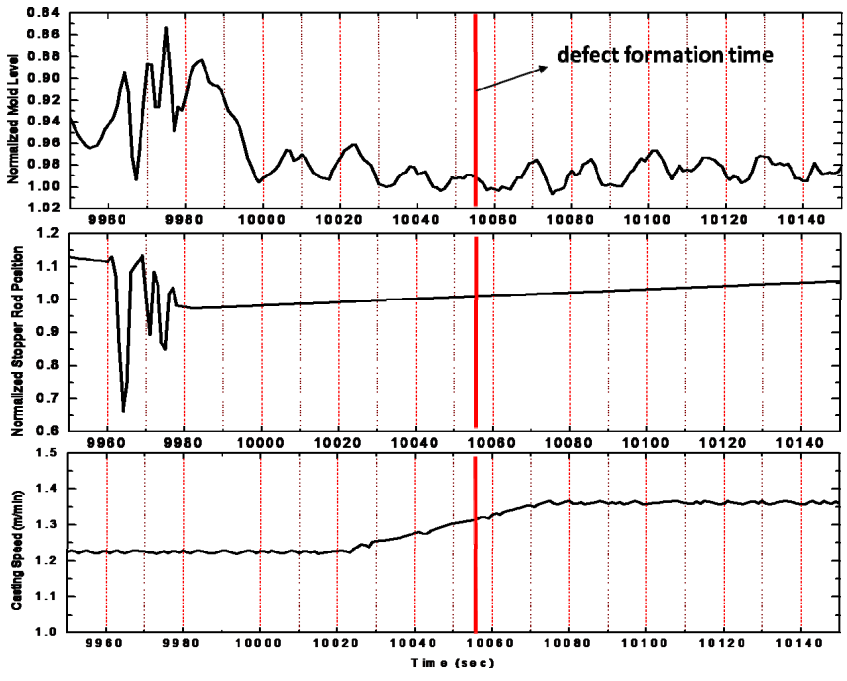
Slide gate oscillates at a certain amplitude with a certain frequency, to avoid clogging and sticking.

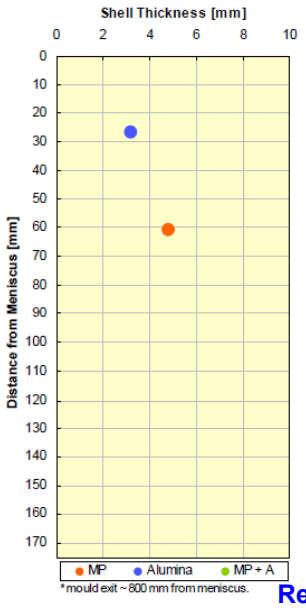


--Figure from

H. Bai and B.G. Thomas, "Two Phase Flow in Tundish Nozzles during Continuous Casting of Steel", Materials Processing in the Computer Age III, V. Voller and H. Henein, eds. 2000.

Background: relevant project:
Transient Flow during Stopper-Rod Movement

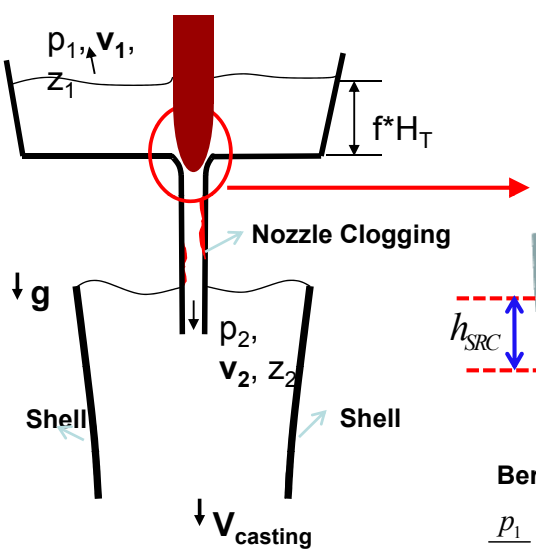


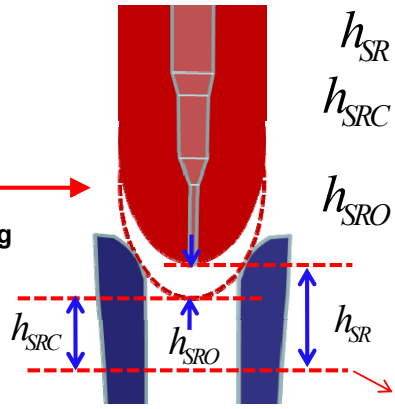


Refs:
R. Liu, CCC Annual Report, 2010;
R. Liu, J. Sengupta, B.G. Thomas. AISTech 2011, Indianaplis

- **Multiple stopper rod movements & mold level spikes (release of clogged material)**
- **Both alumina inclusion and mold powder entrapment were found on coil**

Stopper-position-based Model





h_{SR} : **Stopper Rod Position**

h_{SRC} : **Stopper Rod Zero-Flow Position (closed position)**

h_{SRO} : **Stopper Rod Opening**

$$h_{SRO} = h_{SR} - h_{SRC}$$

Ref:
R. Liu, J. Sengupta, B.G. Thomas. AISTech 2011, Indianaplis

Bernoulli's Equation:

$$\frac{p_1}{\rho g} + z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\rho g} + z_2 + \frac{V_2^2}{2g} + h_{minor} + h_{friction} + h_{clogging}$$

$$\frac{V_{SEN}^2}{2g} + h_{minor} + h_{friction} + h_{clogging} = \left(L_{SEN} - h_{SEN_sub} + f_{tundish} h_{tundish}\right)$$

sub-model 2 sub-model 1 sub-model 3

Variables	Physical Meaning
h_{sen_sub}	SEN submergence depth
$f_{tundish}$	Tundish (weight) fraction
$h_{tundish}$	Total height of the tundish
L_{sen}	Distance from tundish bottom to SEN port center

Metal-level-based Model

Flow rate based on measured casting speed:

$$Q_m(i) = V_{cast}(i) * W * T$$

Ref:
R. Liu, J. Sengupta, B.G. Thomas. AISTech 2011, Indianaplis

SEN Flow rate based on mass conservation from the mold-level signal:

$$Q_E(i) = \frac{h_m(i+1) - h_m(i-1)}{2\Delta t}\left(W * T - \frac{\pi d_{SEN,outer}^2}{4}\right) + Q_m(i)$$

Parameters	Physical Meaning	Parameters	Physical Meaning
h_m	mold level	$d_{SEN,outer}$	outer diameter of SEN
W	mold width	Q_E	SEN flow rate prediction
T	mold thickness	Q_m	Throughput from measured casting speed
Δt	time interval between data points	i	i th time step

Comparison between Two SEN Flow Rate Models

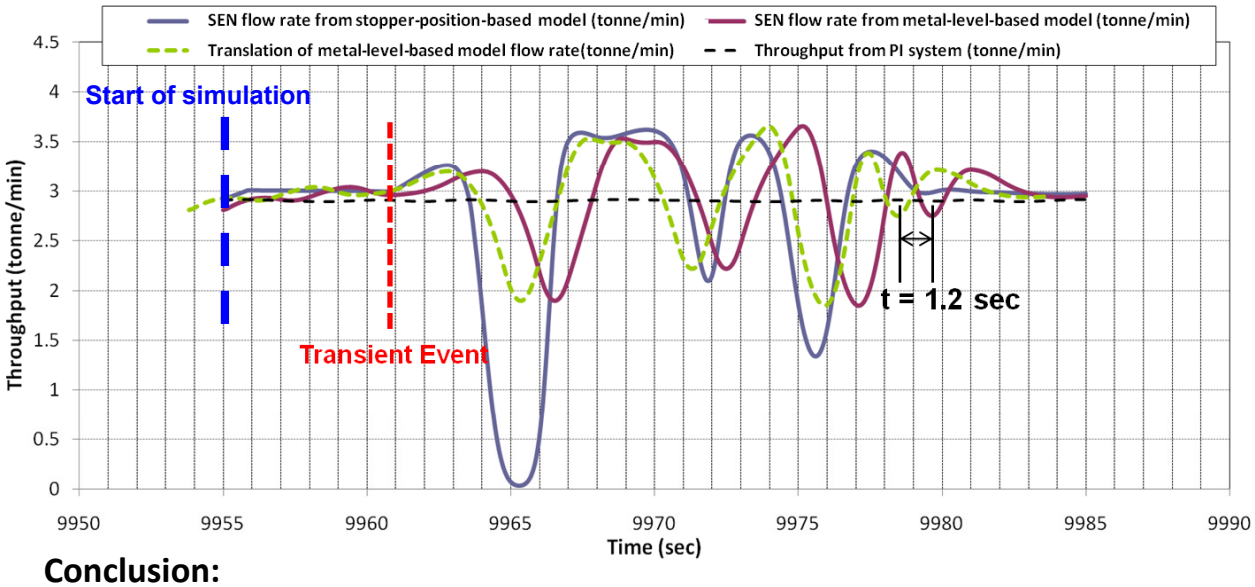
Stopper rod starting position: 46 mm

C_1 = 0.075

C_2 = increasing from 1.8 to 2.2

C_3 = decreasing from 16 to 10

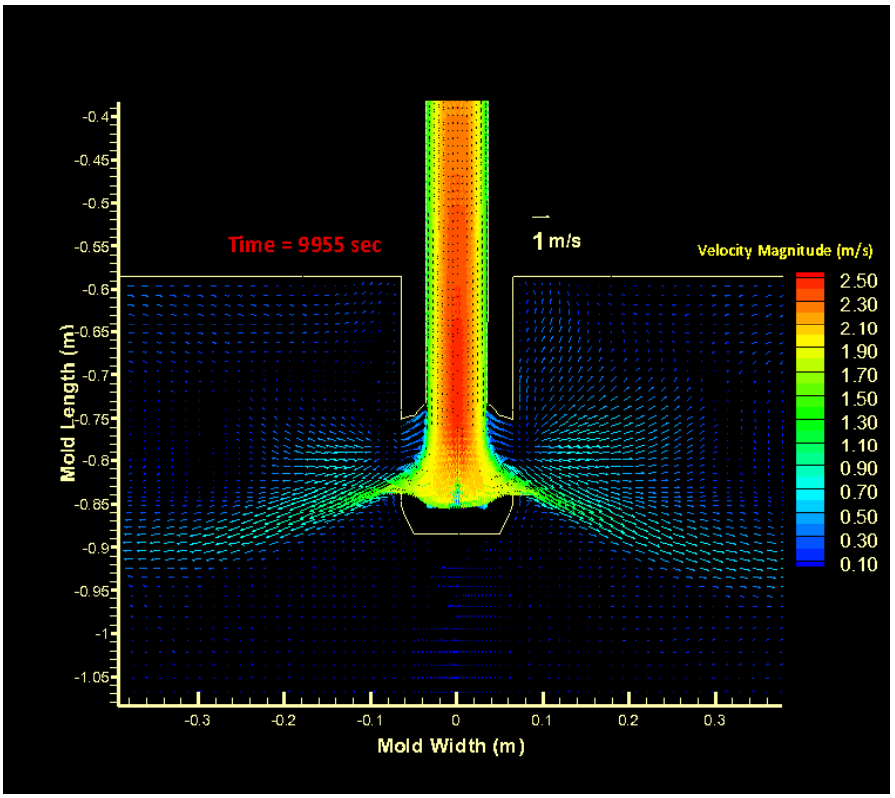
Ref:
R. Liu, J. Sengupta, B.G. Thomas.
AISTech 2011, Indianaplis



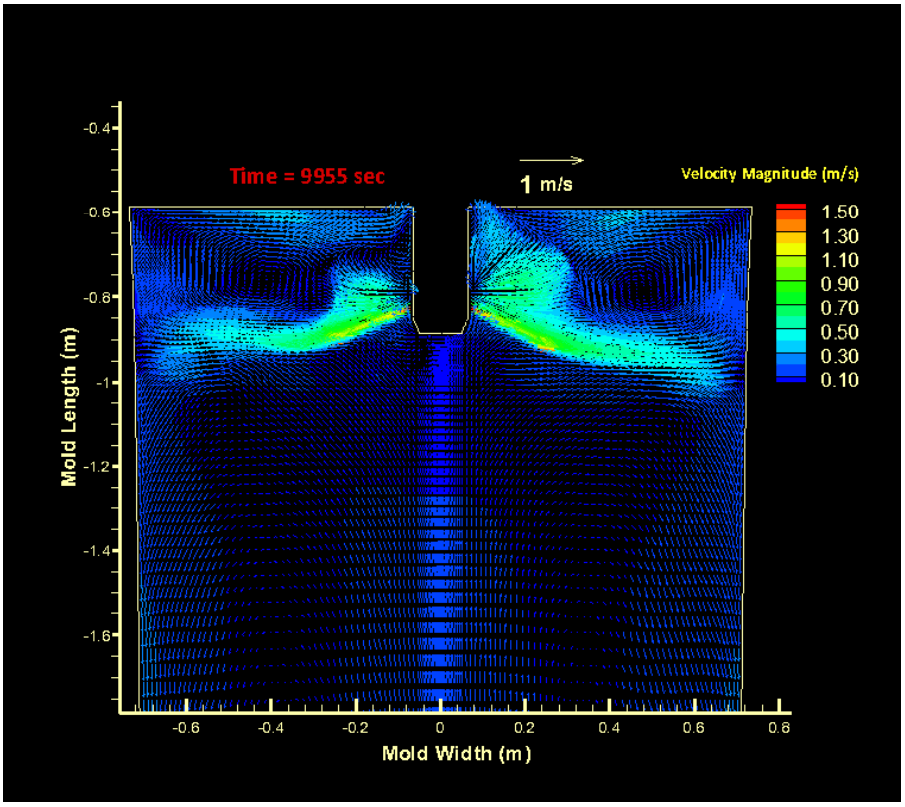
Conclusion:

1.2 sec is the response time lag from stopper to meniscus from observation

Transient Flow at SEN Port Region during Stopper Rod Movement



Transient Flow in the Mold during Stopper Rod Movement

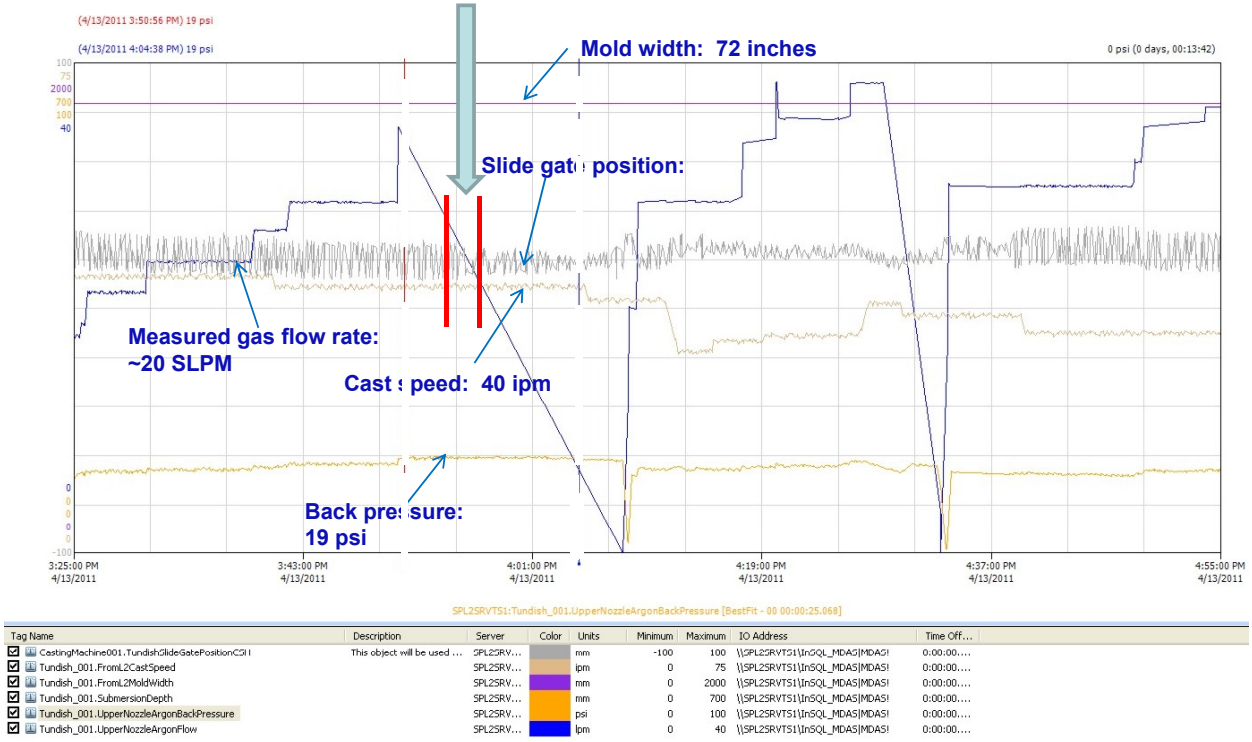


Study on Fluid Flow during Dithering Process -- Modeling Procedure

- **The steps needed prior to modeling the dithering process include:**
  - **choosing a scenario of the dithering process, with mold level and slide gate position data;**
  - **estimating argon flow rate entering heated nozzle;**
  - **obtaining the steady state solution for steel/argon two-phase flow pattern in SEN and mold region, as an initial condition for the dithering simulation;**
  - **converting slide gate position data in the dithering process into liquid steel flow rate/liquid steel inlet velocity data as boundary conditions.**
- **Model assumptions include:**
  - **Half mold used as domain, ignoring left-right bias flow;**
  - **No-slip stationary wall boundary condition at meniscus.**

Step 1: Choosing Scenarios

- **Chosen Scenario for Simulation**

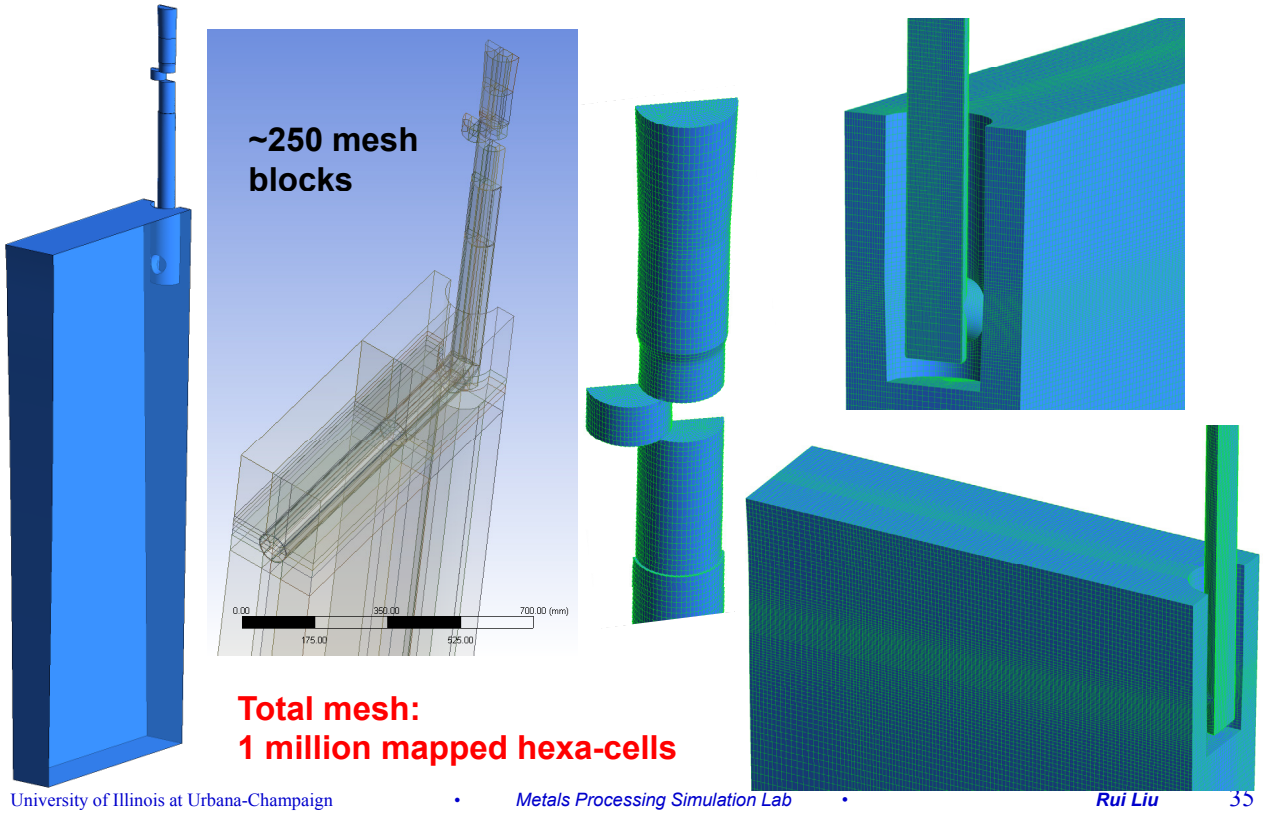


Tag Name	Description	Server	Color	Units	Minimum	Maximum	IO Address	Time Off...
CastingMachine001.TundishSlideGatePositionC9I	This object will be used ...	SPL2SRV...		mm	-100	100	\\SPL2SRVTS1\InSQL_MDAS\MDAS!	0:00:00....
Tundish_001.FromL2CastSpeed		SPL2SRV...		ipm	0	75	\\SPL2SRVTS1\InSQL_MDAS\MDAS!	0:00:00....
Tundish_001.FromL2MoldWidth		SPL2SRV...		mm	0	2000	\\SPL2SRVTS1\InSQL_MDAS\MDAS!	0:00:00....
Tundish_001.SubmersionDepth		SPL2SRV...		mm	0	700	\\SPL2SRVTS1\InSQL_MDAS\MDAS!	0:00:00....
Tundish_001.UpperNozzleArgonBackPressure		SPL2SRV...		psi	0	100	\\SPL2SRVTS1\InSQL_MDAS\MDAS!	0:00:00....
Tundish_001.UpperNozzleArgonFlow		SPL2SRV...		lpm	0	40	\\SPL2SRVTS1\InSQL_MDAS\MDAS!	0:00:00....

Casting Parameters

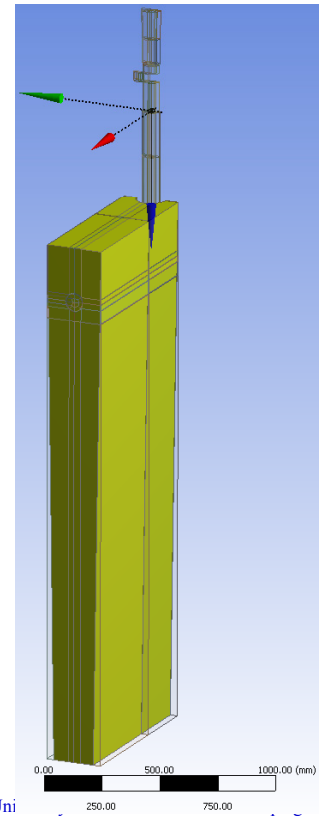
- **Parameters for this process:**
  - Casting speed: **40 ipm**
  - Mold width: **72 inches**
  - Mold thickness: **10 inches**
  - Submergence depth: **8 inches**
  - Dithering amplitude: **14 mm or 7 mm**
  - Dithering frequency: **0.4 Hz**
  - Total gas injection flow rate: **~30 LPM (20 SLPM with 75% leakage based on 19psi back pressure)**
  - SEN bore diameter: **80 mm**
  - Plate diameter: **75 mm**
  - SEN bottom shape: **Cup bottom**
- **Assume 75% leakage based on previous study (R. Liu CCC Annual Report, 2011).**

Geometry and Mesh



Total mesh:
1 million mapped hexa-cells

Computation Details



Models and Schemes	Name
Turbulence Model	k-epsilon with std. wall functions
Multiphase Model	Eulerian Model
Advection Discretization	1st order upwinding

B.C.:	Meniscus	Domain Outlet
	No-slip wall	Pressure outlet

Bubble size: 2.4 mm **Time step:** 0.05 sec

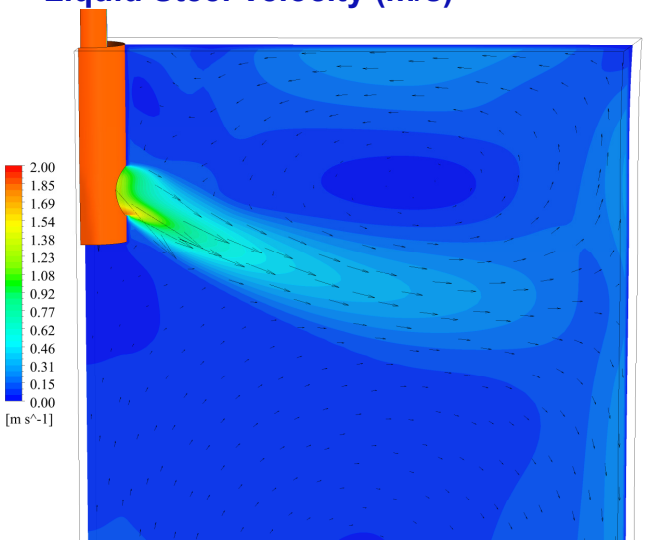
Total mesh: 1.0 million mapped hexa- cells

Sources and Sinks:
Mass and momentum sinks are utilized for solidification of liquid steel adjacent to shell, and escape of argon gas adjacent to meniscus

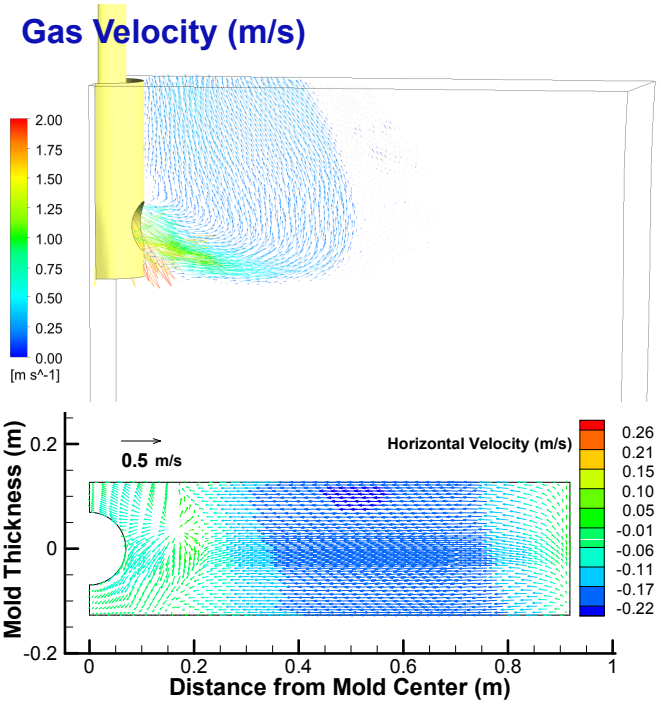
Half mold was used as computational domain.

Step 3: Liquid Steel/Argon Flow Patterns –Initial Field for Dithering

Liquid Steel Velocity (m/s)



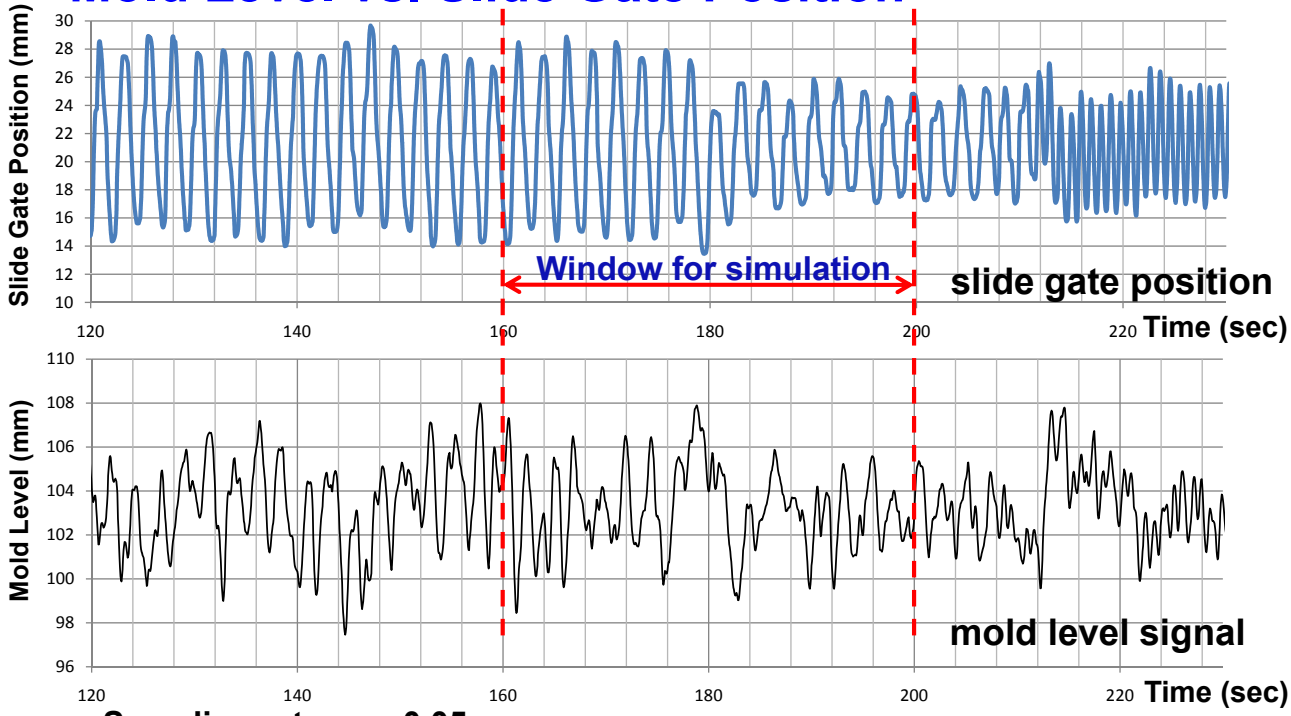
Gas Velocity (m/s)



30 LPM argon flow rate
(hot condition, from porous flow model)

Step 4: Converting Slide-gate Position Data into Velocity Input

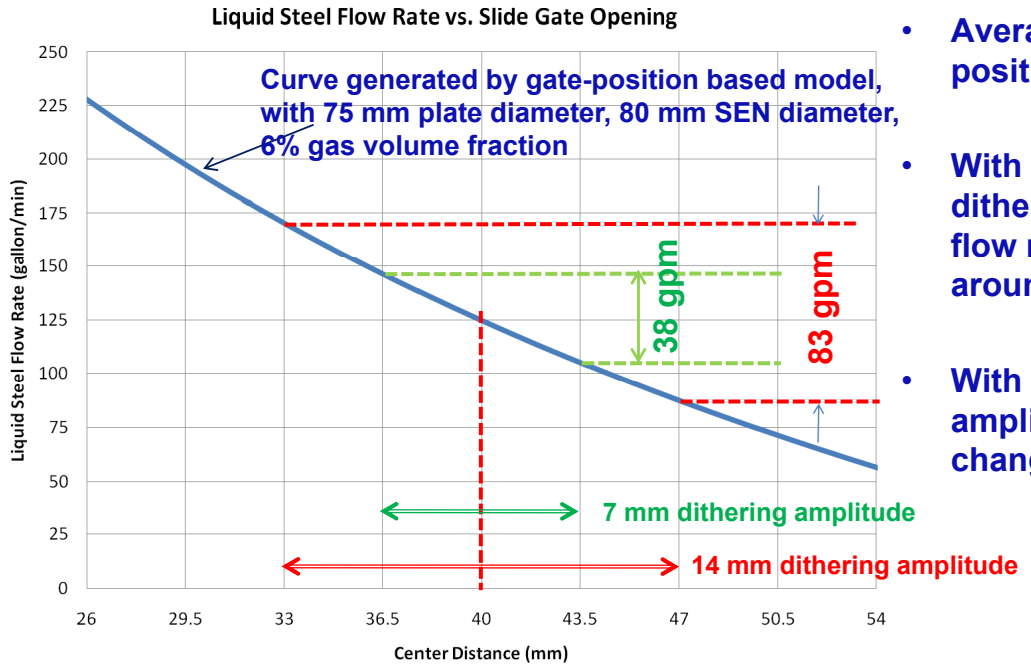
- **Mold Level vs. Slide Gate Position**



Sampling rate: per 0.05 sec

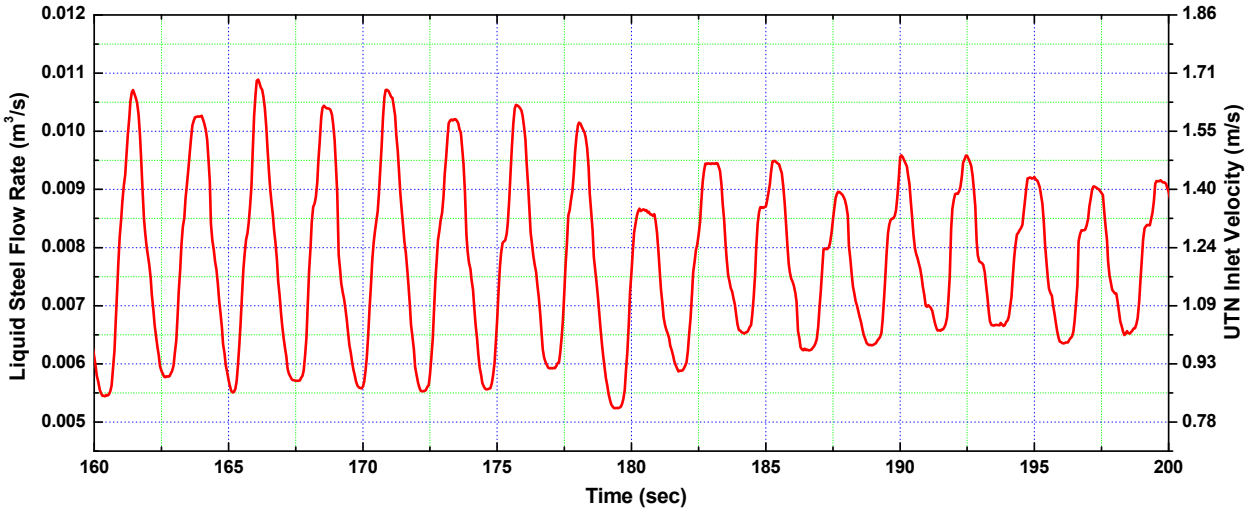
--Un-filtered data from K. Zheng and B. Umlauf

Flow Rate Change during Dithering Process



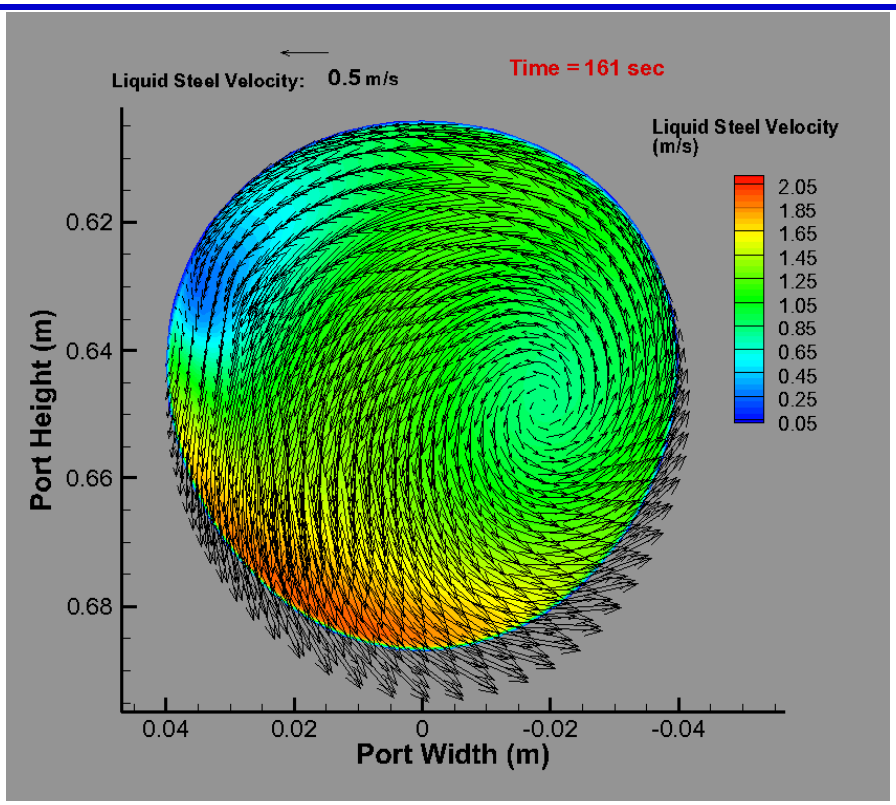
- Average slide gate position is 40 mm;
- With 14 mm dithering amplitude, flow rate change is around 83 gpm;
- With 7 mm dithering amplitude, flow rate change is 38 gpm.

Dithering Simulation —Velocity Input

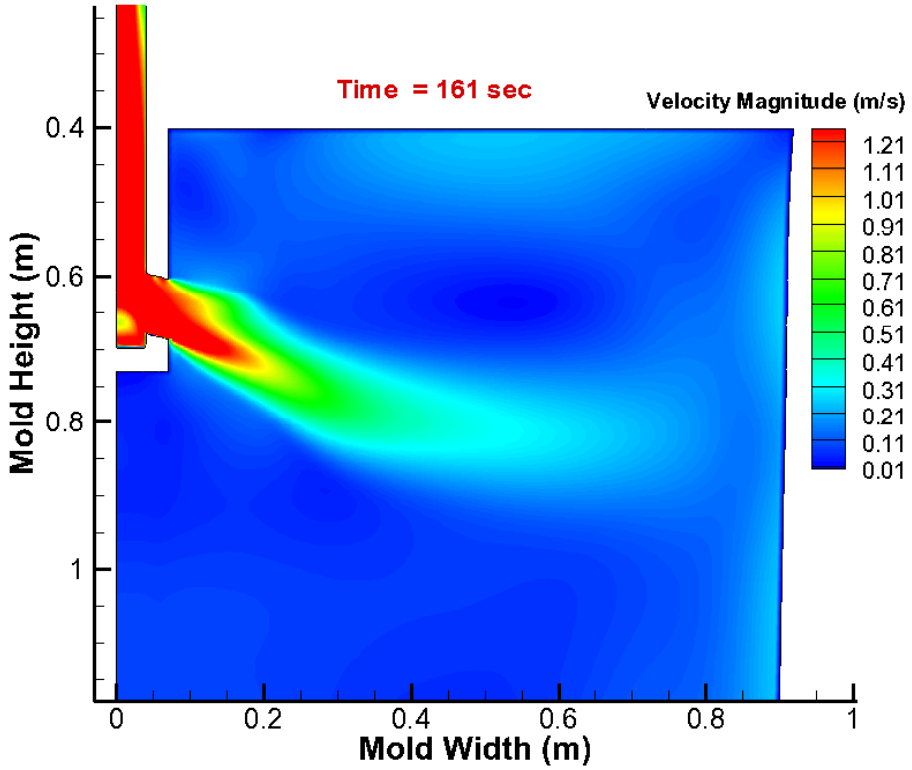


Time step in the simulation is the same as the sampling time interval: 0.05 sec

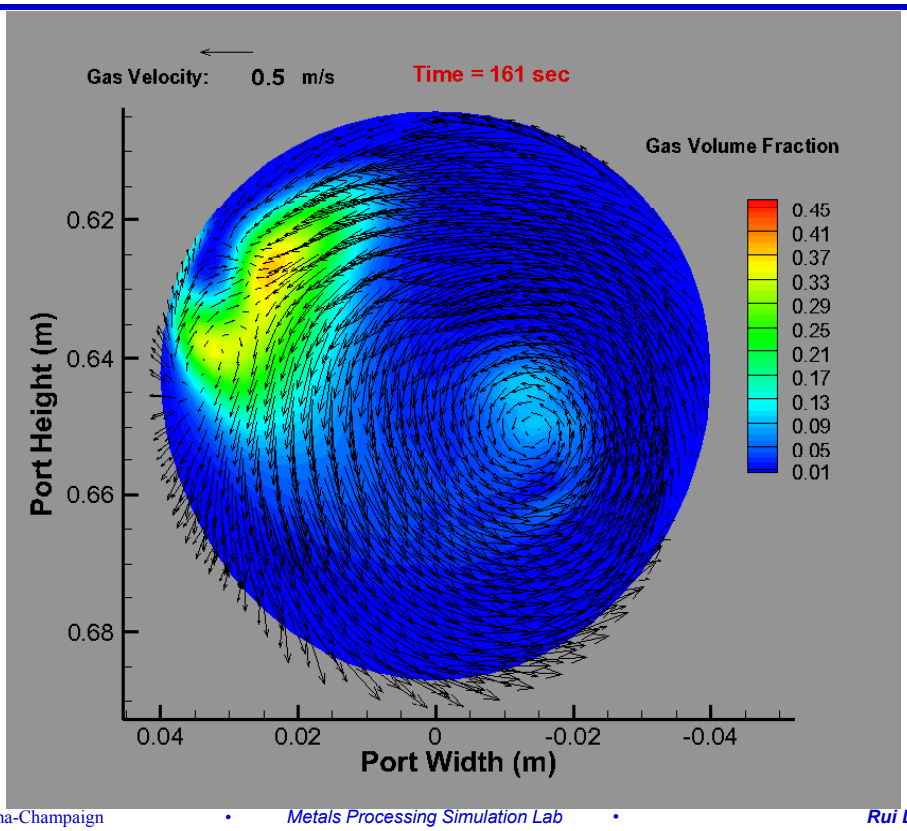
Liquid Steel Velocity Distribution at SEN Port Exit



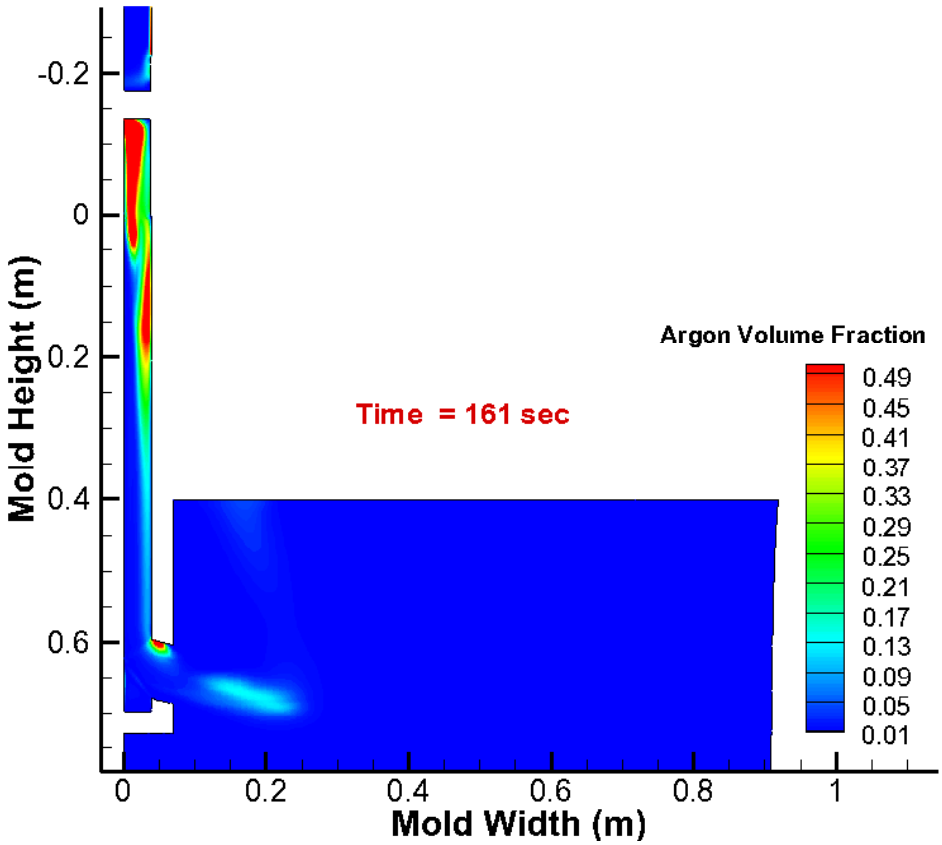
Liquid Steel Flow Pattern during Dithering Process



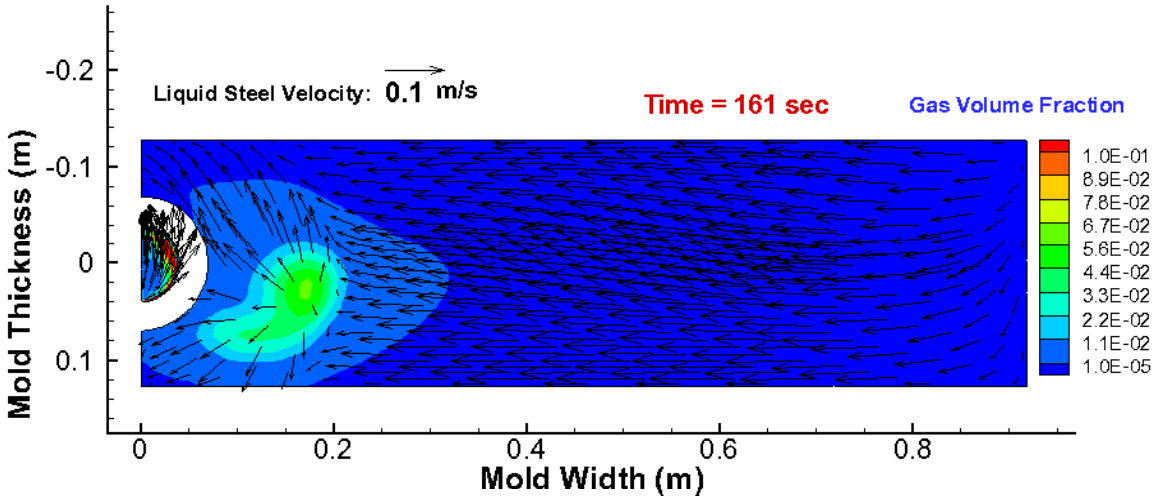
Argon Velocity/Volume Fraction Distributions at SEN Port Exit



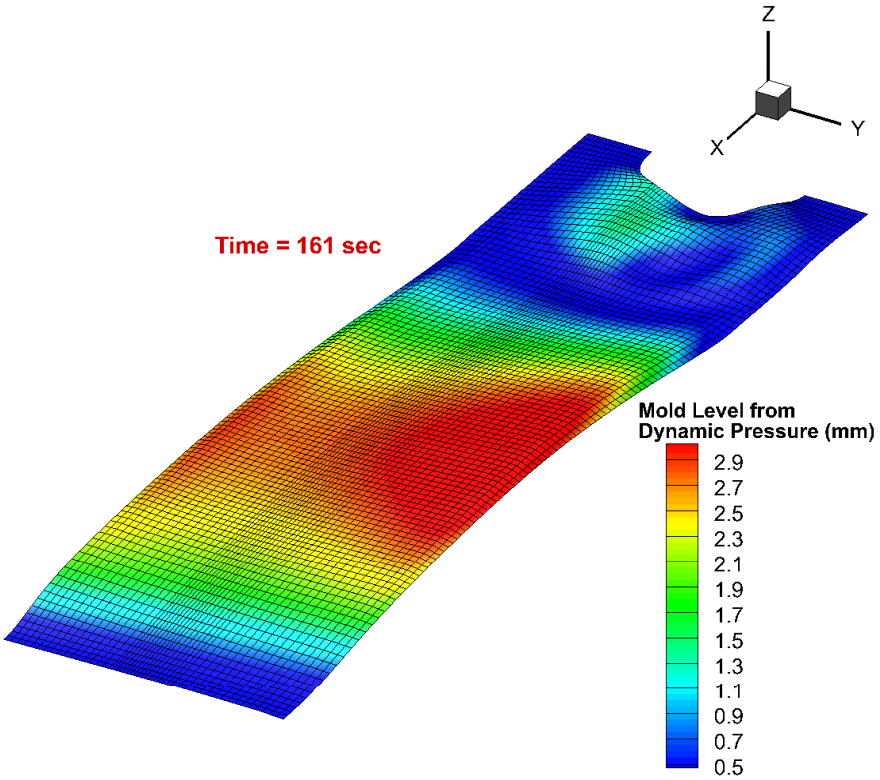
Argon Distribution during Dithering Process



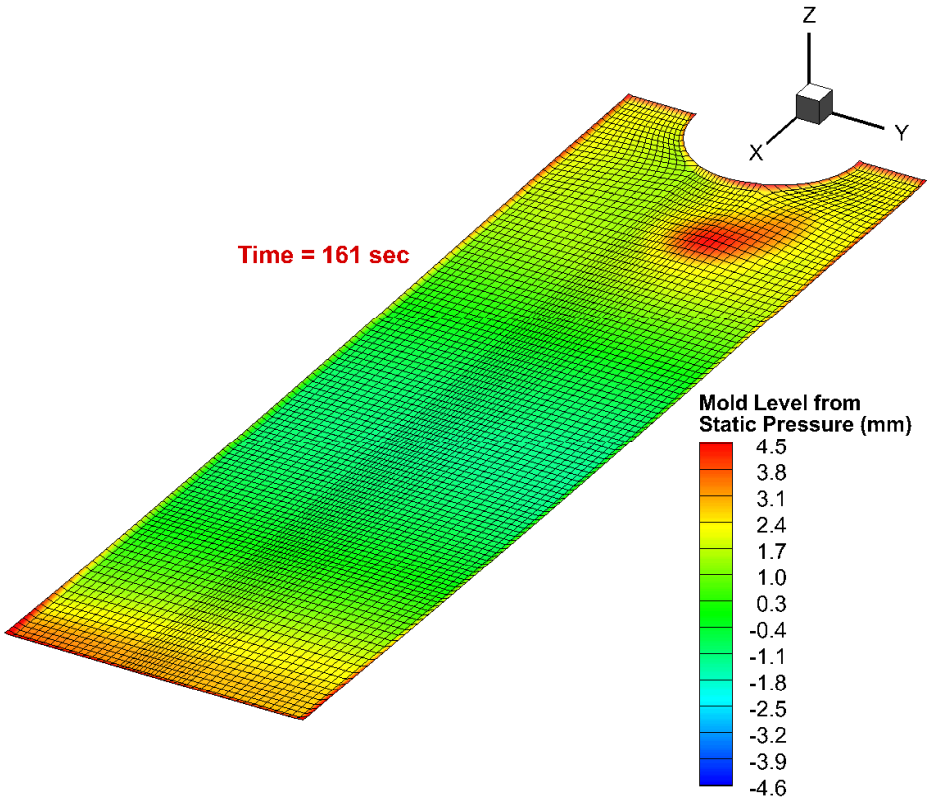
Liquid Steel Velocity/Argon Volume Fraction Distributions at Meniscus



Mold Level Fluctuation –Jet Dynamics



Mold Level Fluctuation –Mass Conservation



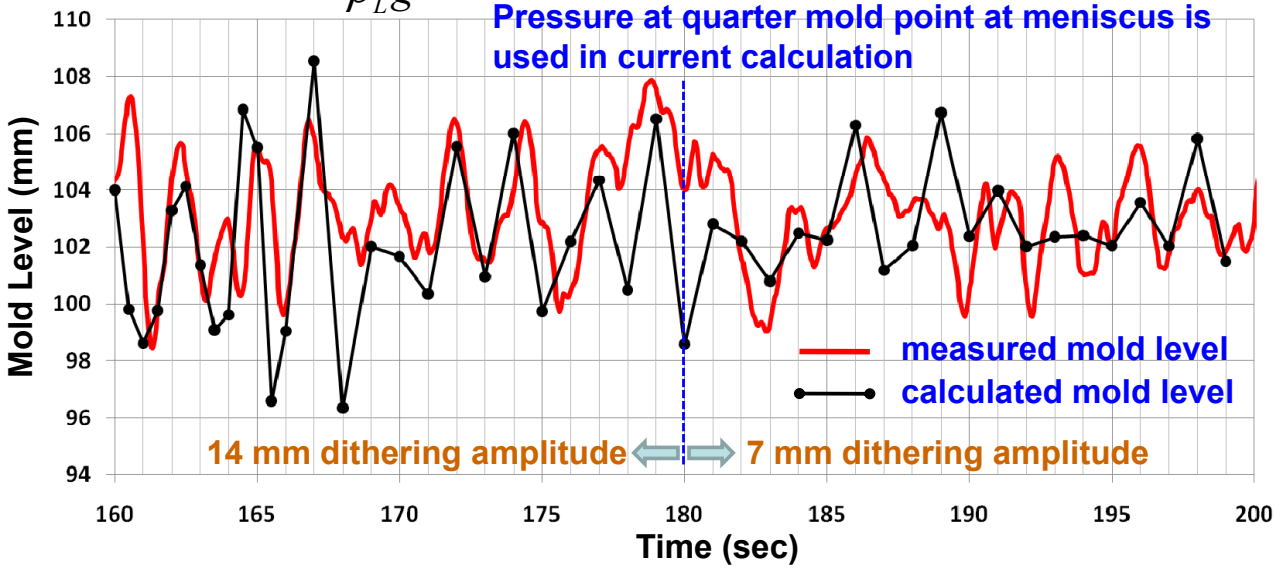
Calculated vs. Measured Mold Level

- **Mold level is calculated using a pressure method:**

$$\Delta h = \frac{p - p_0}{\rho_L g}$$

p_0 is the static pressure at starting time (160 sec in current case)

Pressure at quarter mold point at meniscus is used in current calculation



Calculated mold level matches well with the measured mold level, which also validates the computational model.

Conclusions –Part 3

- Methodology has been developed to simulate fluid flow patterns during dithering process, adopting the following models:
  - gas flow through heated refractory for gas flow rate prediction
  - gate-position-based model for liquid steel flow rate prediction
- Simulation shows jet wobbling and periodical change of meniscus velocities responding to the slide gate dithering process;

Conclusions –Part 3 (cont.)

- Computational model has been validated by comparing the measured mold level with calculated mold level, which reveals:
  - pressure method is valid to calculate mold level in transient applications such as dithering where the fluctuations are not too severe;
  - mold level oscillates periodically during dithering process, with the same frequency as the dithering frequency;
  - mold level fluctuation magnitude is proportional to the gate dithering magnitude;
  - the major mechanism that dominates meniscus fluctuation during dithering process is the mass conservation of the system (especially when the dithering amplitude is high).

Future Work

- Large Eddy Simulation (LES) of two phase flow (Eulerian-Lagrangian model to track bubbles) in water model and real caster;
- More validation work on transient simulations (mold level, sub-surface velocity measurements, PIV, etc.);
- Simulate other transient scenarios to further understand mechanisms of defect formation and finally help set up operation guidelines

Acknowledgements

- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Tata Steel, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech, Posco, SSAB, ANSYS-Fluent)
- I want to thank:
  - Bernard for offering me the second FLUENT license during my internship;
  - Hongbin for all the discussions and help with everything;
  - Bruce for providing water model exp. Data and teaching me about hydraulic system;

Acknowledgements (Cont.)

- Kai Zheng and Bill Umlauf for the helpful discussions and providing me with mold level data during dithering process
- Jeff for helping me out with water model experiments
- Yong for all the helpful discussions and teaching me about refractory;