ANNUAL REPORT 2012

UIUC, August 16, 2012

Slide-gate Dithering Effects on Transient Flow and Mold Level Fluctuations

R. Liu and B.G. Thomas

Department of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign

ArcelorMittal Global R&D
at East Chicago

Outline

- **Free surface modeling using moving grid technique with FVM approach (developed via UDF in FLUENT)**
  - **Model development and validation**
  - **Model application with previous dithering simulation**
- **Modeling transient fluid flow in CC SEN/mold region**
  - **Boundary conditions for CFD simulation in CC process**
    - **Flow rate prediction using gate-position-based model – inlet**
    - **Free surface simulation during dithering – top surface**
    - **Modification of mass and momentum equations – shell**
    - **Pressure Modification – domain outlet**
  - **Simulated flow pattern and free surface evolution**
- **Parametric study on mold level fluctuation during dithering using the flow rate model**

Part 1

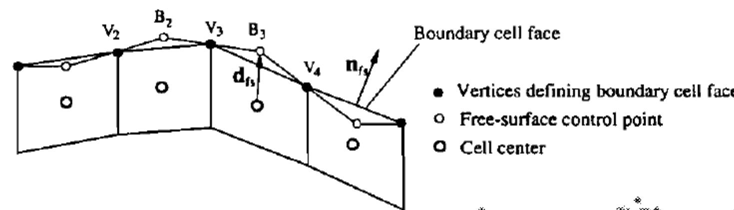
Free Surface Modeling using a Moving Grid Technique

- **Mold free surface must be modeled together with argon-steel multiphase flows to:**
  - **study the gravity wave effects during dithering;**
  - **difficulty rises in adopting both VOF and Eulerian-Eulerian models in the simulation using FLUENT;**
  - **a simple, accurate and computational efficient interface-tracking model must be developed to model free surface motion together with multiphase flow simulation during dithering.**
- **In current work, an interface tracking model is developed in FLUENT using the moving grid technique:**
  - **local mass conservation is enforced by moving the nodes properly following the Spatial Conservation Law (SCL);**
  - **both kinematic and dynamic boundary conditions are directly applied in the model to solve the momentum equations;**
  - **mesh smoothing is performed to ensure a good mesh quality.**

Moving Grid Technique using FVM

Continuity equation with moving mesh:

$$\nabla \cdot \left(\rho \left(\mathbf{v} - \mathbf{v}_g \right) \right) = 0$$



$$\dot{m}_{fs} + \rho \dot{V}'_{fs} = 0$$

Momentum equation with moving mesh:

$$\frac{\partial \left(\rho \mathbf{v} \right)}{\partial t} + \nabla \cdot \left(\rho \mathbf{v} \left(\mathbf{v} - \mathbf{v}_g \right) \right) = -\nabla p + \nabla \cdot \left(\mu \nabla \mathbf{v} \right) + \mathbf{F}$$

V is fluid velocity, while V_g is grid velocity (mesh velocity)

$$\Delta h = \gamma_{fs} \frac{\dot{V}'_{fs} \Delta t}{S_{fs} \mathbf{n} \cdot \mathbf{e}_{fs}}$$

$$\mathbf{r}_{B_i}^{k+1} = \mathbf{r}_{B_i}^{k} + \Delta h \, \mathbf{e}_{fs}$$

$$\mathbf{r}_{V_i}^{k+1} = \mathbf{r}_{V_i}^{k} - \mathbf{e}_{fs} \cdot \left[\mathbf{r}_{V_i}^{k} - \sum_{m=1}^{n} w_m \mathbf{r}_{B_m}^{k+1} \right] \mathbf{e}_{fs}$$

Kinematic B.C.:

$$\left[\left(\mathbf{v} - \mathbf{v}_s \right) \cdot \mathbf{n} \right]_{fs} = 0 \quad \text{or} \quad \dot{m}_{fs} = 0$$

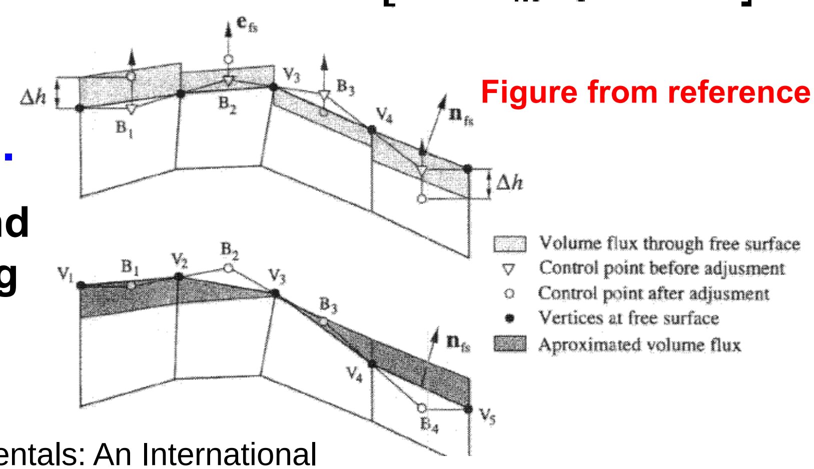


Figure from reference

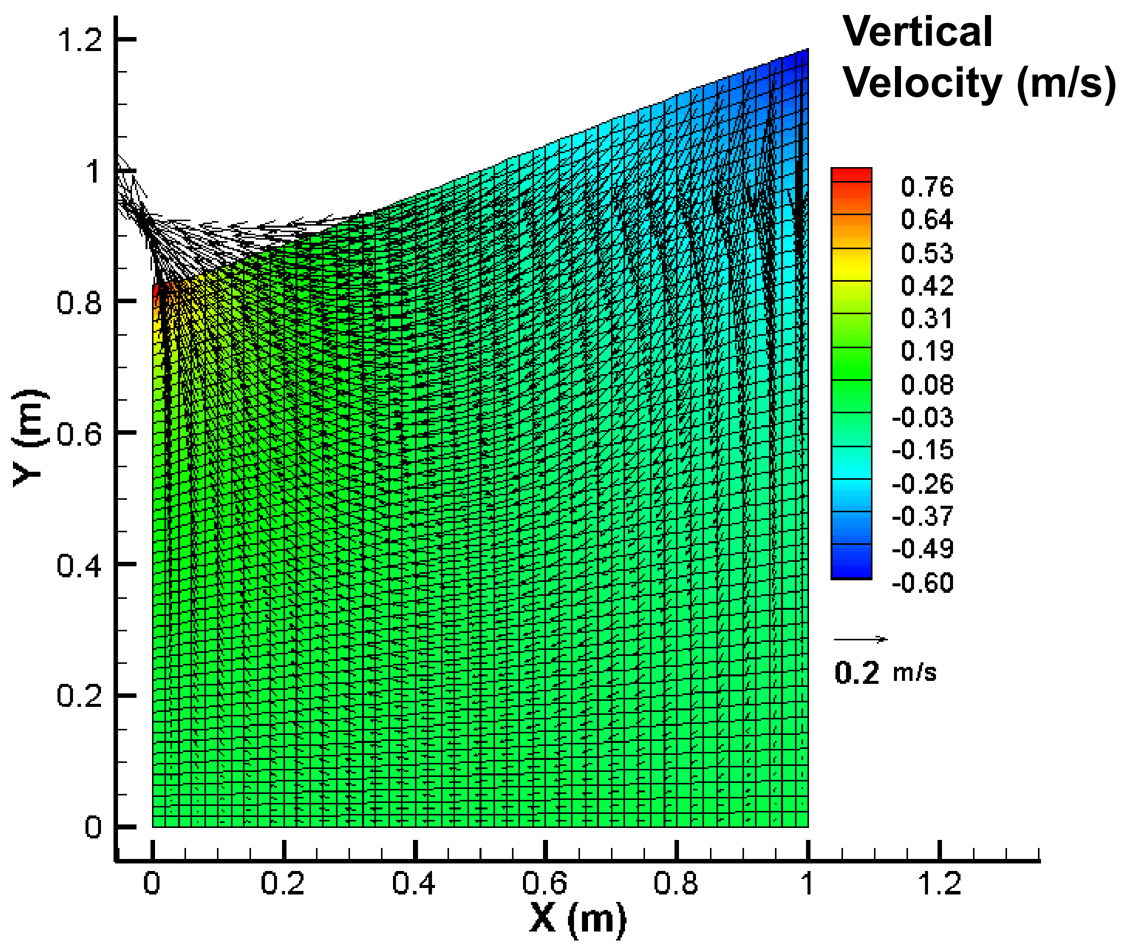
Dynamic B.C.: all forces in equilibrium at fs.

This node moving approach has been adopted and coded into FLUENT UDF for free surface modeling in current work

Ref:

S. Muzaferija and M. Peri´c, Numerical Heat Transfer, Part B: Fundamentals: An International Journal of Computation and Methodology, 1997. Vol 32:4, 369-384

Large Amplitude Sloshing



Example Problem:

Viscous liquid is filled in a long trapezoid-shaped container. The top wall of the container suddenly gets removed, and liquid is released to gravity

- **Free surface nodes moved via UDF, with kinematic and dynamic B.C.s satisfied**
- **Side wall nodes and internal nodes are smoothed via solution of a Laplace equation diffusing free surface nodes displacements to interior nodes**

Model Validation – Analytical Solution and Case Setup

- **2-D small-amplitude sloshing problem**

$$a(t) = \frac{4\nu^2 k^4}{8\nu^2 k^4 + \omega_0^2} a_0 erfc\left(\nu k^2 t\right)^{\frac{1}{2}} + \sum_{i=1}^{4} \frac{z_i}{Z_i}\left(\frac{\omega_0^2 a_0}{z_i^2 - \nu k^2}\right)\exp\left(\left(z_i^2 - \nu k^2\right)t\right) erfc\left(z_i t^{\frac{1}{2}}\right)$$

Where z_i is the i^{th} root of the equation below, and z_i is defined as:

$$z^4 + 2\nu k^2 z^2 + 4\left(\nu k^2\right)^{\frac{3}{2}} z + \nu^2 k^4 + \omega_0^2 = 0 \qquad \omega_0 = \sqrt{gk}$$

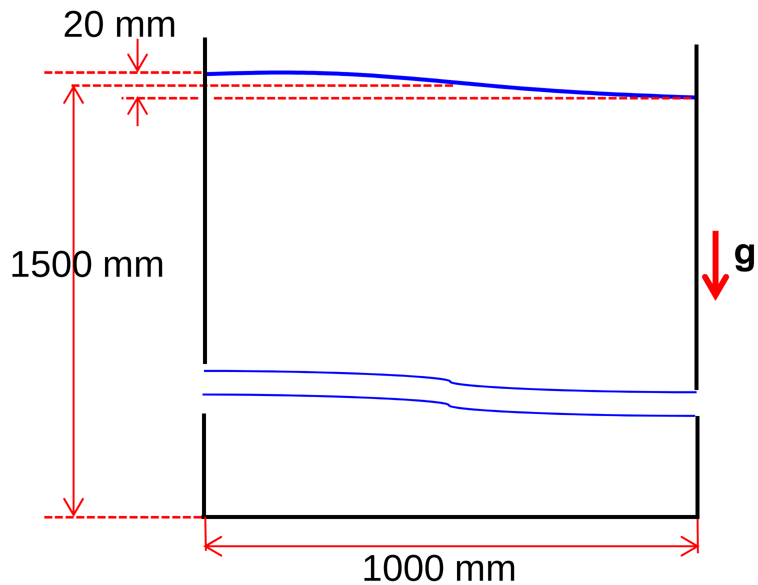
Prosperetti, A., 1981. "Motion of two superposed viscous fluids". Physics of Fluids, 24(7), July, pp. 1217–1223.

Initial Interface: $h(x) = 1.5 + a_0 \sin\left(\pi(0.5 - x)\right)$

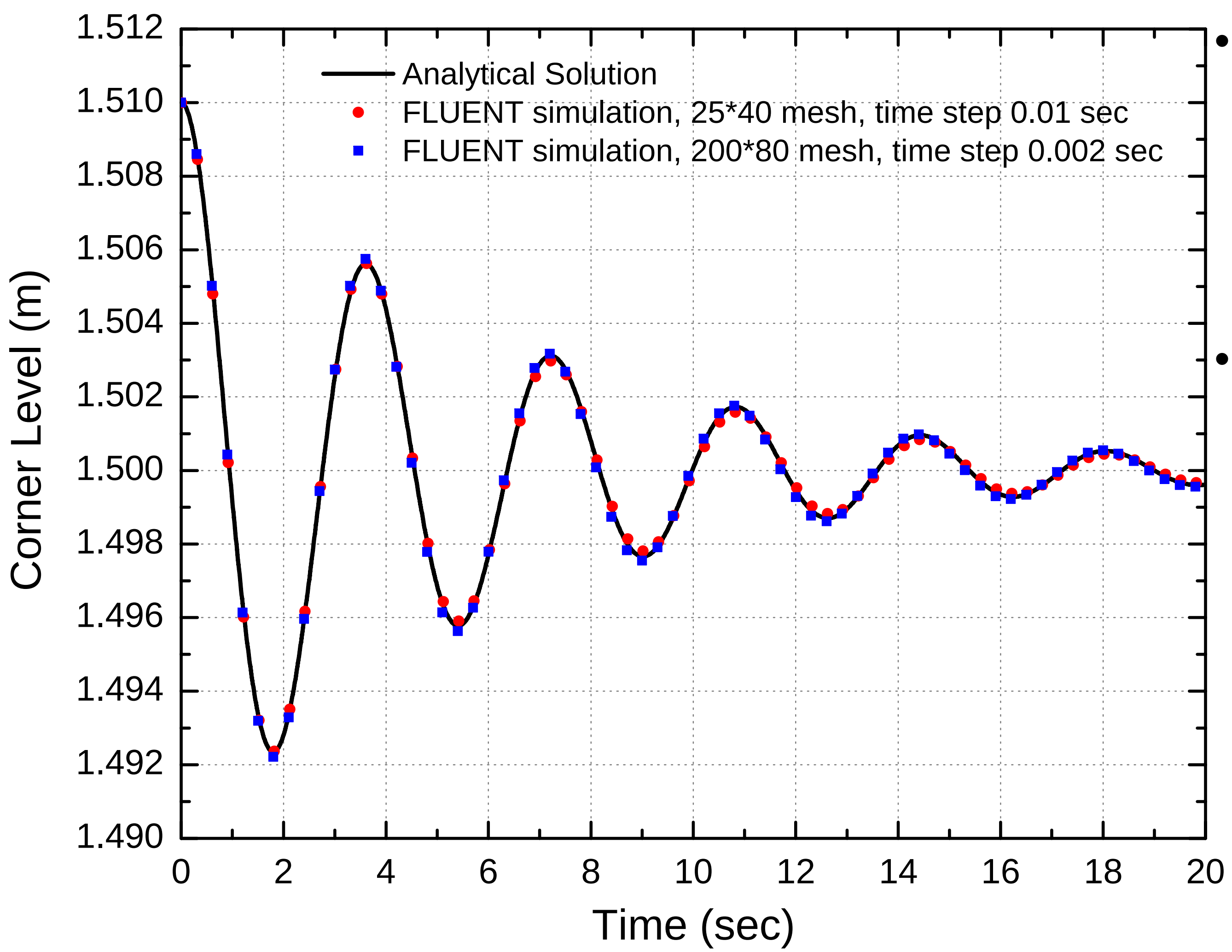
a_0=0.01 m

Level Height (mm)	Tank Width (mm)	Initial Perturbation Amplitude (mm)
1500	1000	20

Fluid Kinematic Viscosity (m²/s)	Gravity Acceleration (m/s²)	Surface Tension (N/m)
0.01	1.0	0



Model Validation – Comparison with Analytical Solution



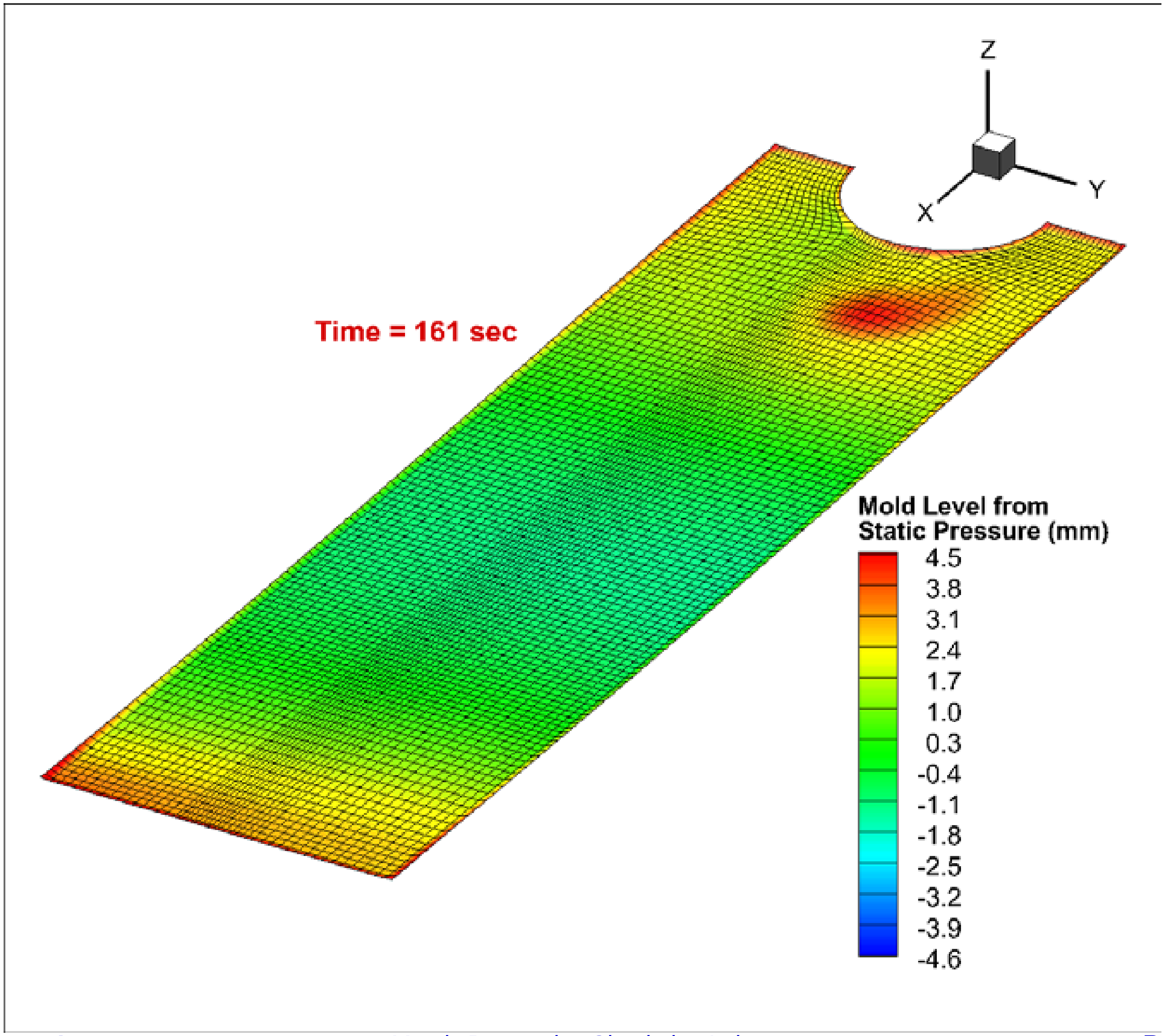
- **Excellent match with analytical solution obtained even for simulations using the very coarse mesh**
- **Using second order (or higher) advection scheme and temporal scheme are crucial for achieving accuracy**

Application to Simulate Dithering with Gas Injection

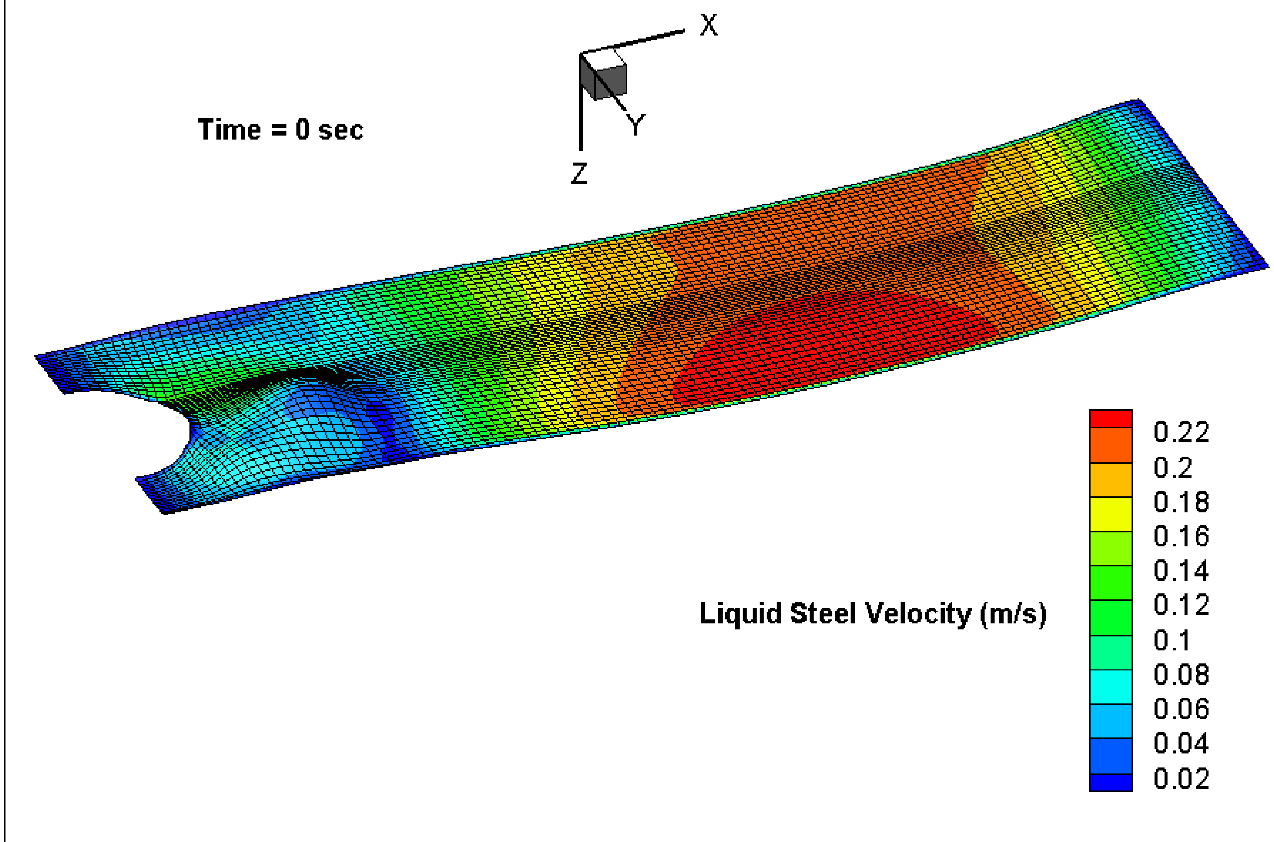
- **Casting parameters:**
  - Casting speed: **40 ipm**
  - Mold width: **72 inches**
  - Mold thickness: **10 inches**
  - Submergence depth: **8 inches**
  - Dithering amplitude: **14 mm or 7 mm**
  - Dithering frequency: **0.4 Hz**
  - Total gas injection rate: **30 LPM** (20 SLPM with 75% leakage based on 19psi back pressure [1])
  - SEN bore diameter: **80 mm**
  - Plate diameter: **75 mm**
  - SEN bottom shape: **Cup bottom**

[1] (R. Liu and BG Thomas, *AISTech 2012*, (Atlanta, GA, May 7-9, 2012).

Free Surface Movement – Pressure Method



Free Surface Movement – Moving Grid



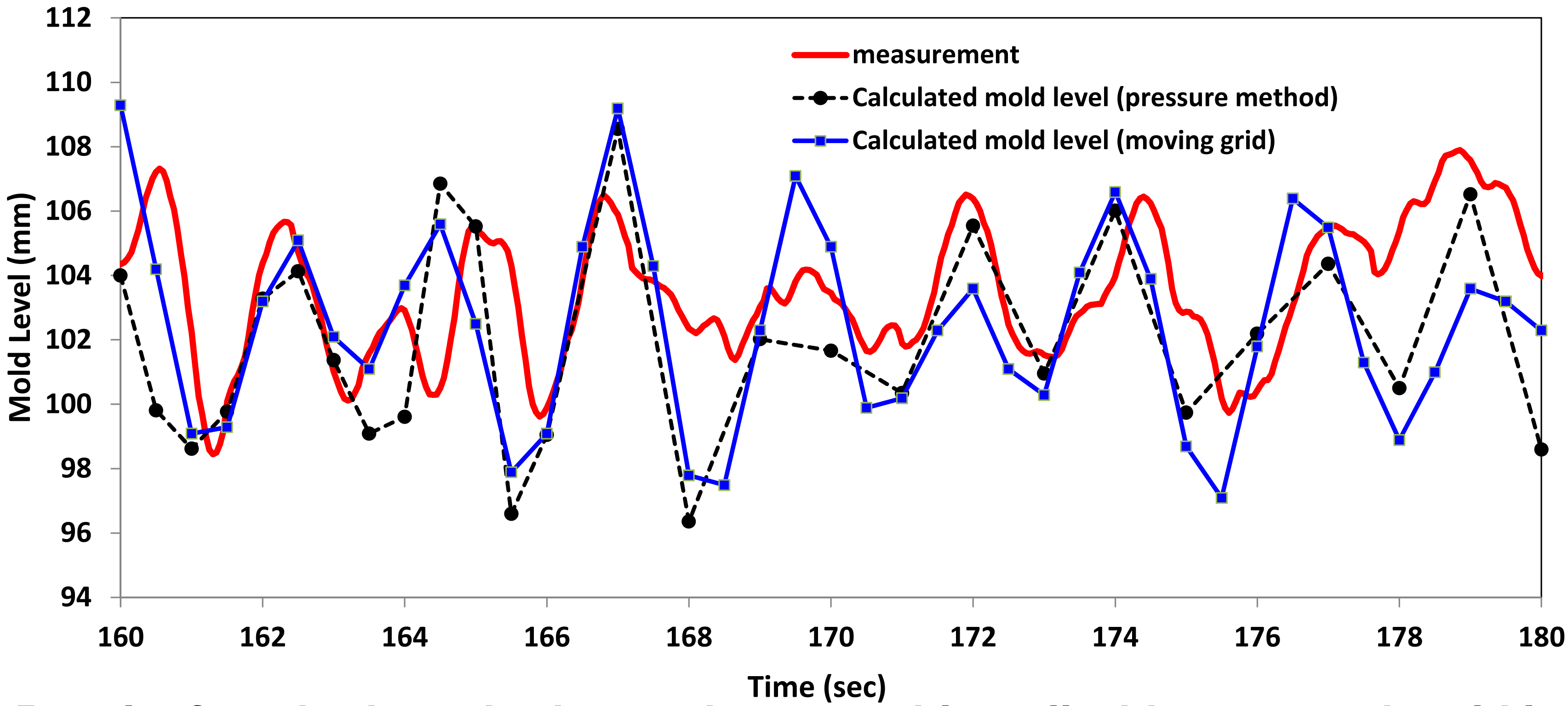
Comparison of Simulated and Measured Mold Level

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



- **Results from both methods match reasonably well with measured mold level**

Comparison of Free Surface Capturing Methods

- **Pressure method**
  - easiest to obtain, used only for post-processing
  - unable to model gravity waves
- **Volume of Fluid (VOF)**
  - fixed Eulerian mesh
  - smearing interface due to numerical diffusion from volume fraction equation
  - small time step required for stability restriction in explicit marching (expensive)
- **Moving grid technique (in FVM)**
  - moving mesh representing domain deformation (mixed Eulerian and Lagrangian mesh)
  - sharp interface directly obtained from mesh
  - cannot predict entrainment of the secondary phase

Conclusion – Part 1

- **A free surface model with moving grid technique is developed in FLUENT via UDF based on its "dynamic mesh" feature.**
- **The free surface model has been validated using:**
  - **the small amplitude sloshing analytical solution, which proves that the model is accurate even with relative coarse mesh;**
  - **mold top surface motion during CC dithering process, which shows:**
    - **the capability of the model to simulate free surface behavior under gravity waves;**
    - **the model can be used together with Eulerian-Eulerian multiphase flow models to study free surface behavior in cases with argon injection into the CC mold**

Part 2

Modeling Transient Flows and Free Surface during the Dithering Trial

- List of Cases from ArcelorMittal Indiana Harbor 3SP dithering trial;
- Calculation of sloshing frequency
  - a rectangular tank (3-D solution);
  - an infinite deep channel (2-D solution).
- Computation of dithering effects on mold flow pattern and mold level fluctuations
  - computational model setup;
  - quasi-steady state flow pattern and free surface deformation;
  - flow and free surface evolution during dithering.

ArcelorMittal Indiana Harbor Dithering Trial

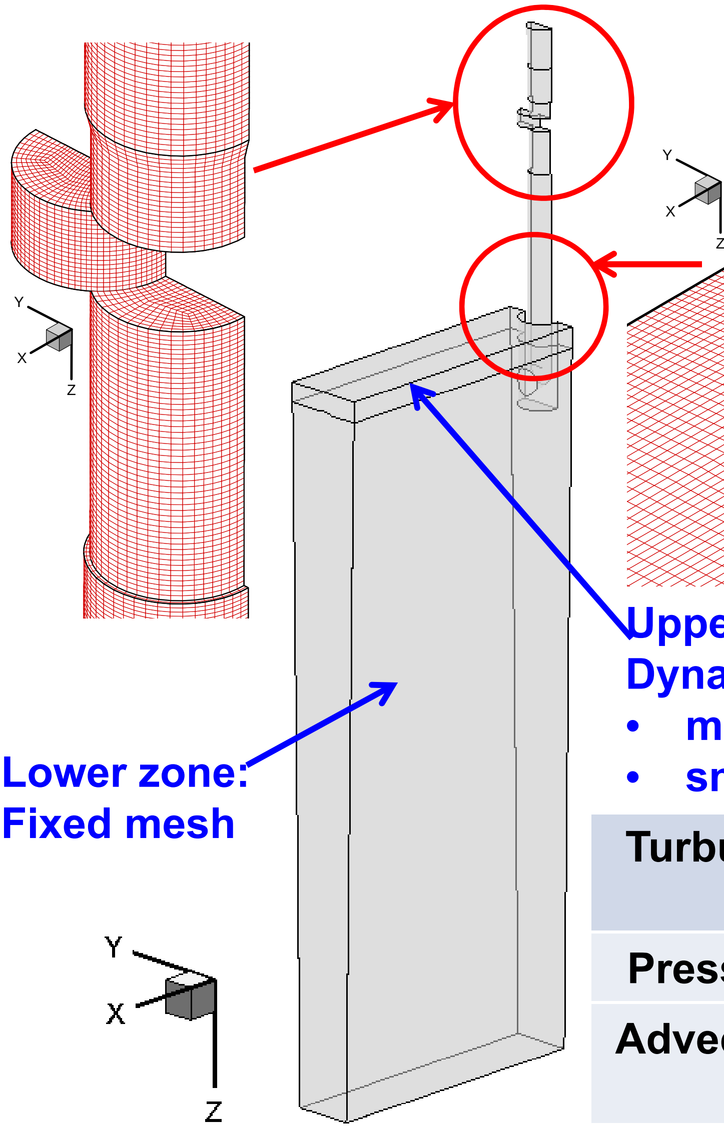
- **Casting parameters for the dithering trial:**
  - Casting speed: 40 ipm
  - Mold width: 72.5 inches
  - Mold thickness: 10 inches
  - Submergence depth: 5.6 inches
  - Total gas injection flow rate: 1 SLPM (1% in hot condition)
  - SEN bore diameter: 80 mm
  - Plate diameter: 75 mm
  - SEN bottom shape: Roof bottom

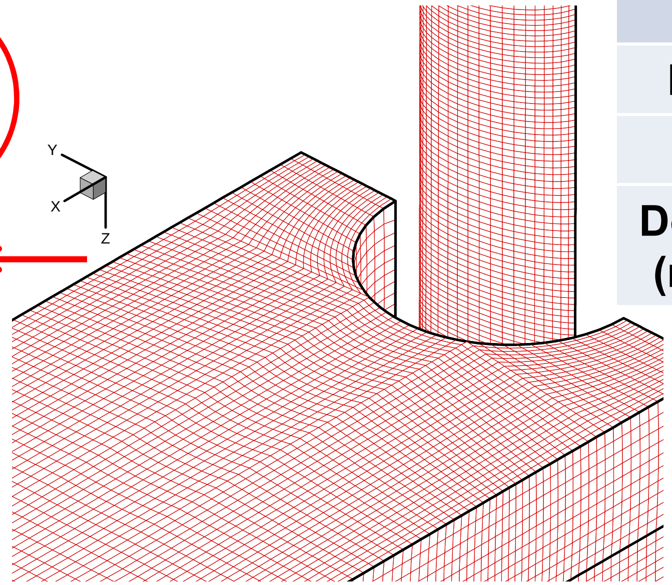
Case #	Frequency (Hz)	Stroke (mm)	Mold Operator Comments
1	0.6	14	Not many waves
2	0.8	14	More waves than 0.6 Hz
3	0.9	14	Giant sloshing, worst level scenario
4	1.0	14	More waves than 0.8 Hz
5	1.2	12	No waves in the mold, best frequency
6	1.4	7	Very few waves, but 1.2 Hz is better

Numerical Simulation

- Domain geometry and mesh
- Computation condition:
  - Numerical parameters
  - Turbulence models
  - Discretization scheme
  - Boundary conditions
- Quasi-steady state solution
- Flow field evolution during dithering process – simulating trial case 3

Computational Domain and Mesh





Time Step	0.005 sec
Mesh Count	1.5 million
Cell Shape	Hexahedral
Domain Height (mold region)	2.5 m

Assumptions:

1. Half mold was used as computational domain (neglecting left-right flow asymmetry)
2. Iso-thermal flow

Upper zone:
Dynamic mesh zone,
- moving grid at top surface
- smoothing the mesh elsewhere

Lower zone:
Fixed mesh

Turbulence Model	1. k-ω with std. wall functions 2. Detached Eddy Simulation (DES)
Pressure Scheme	body force based
Advection Scheme	1. 2^{nd} order upwinding 2. Bounded Central Differencing

Flow Rate Calculation – Inlet B.C.

Equation for gate-position-based model (including gas effect):

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

where $\mu = 0.63 + 0.37\left(\frac{A_{GAP}}{A_{SG}}\right)^3$ $\quad A_{eff} = \begin{cases} A_{SEN} & \textbf{single phase flow} \\ \dfrac{V_c WT}{Q_{gas}+V_c WT}A_{SEN} & \textbf{two phase flow} \end{cases}$

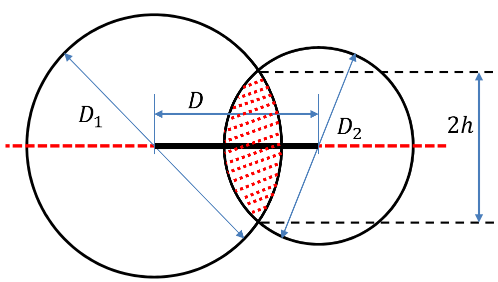
For continuous caster, an extra term should be added to account for pressure drop due to clogging:

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

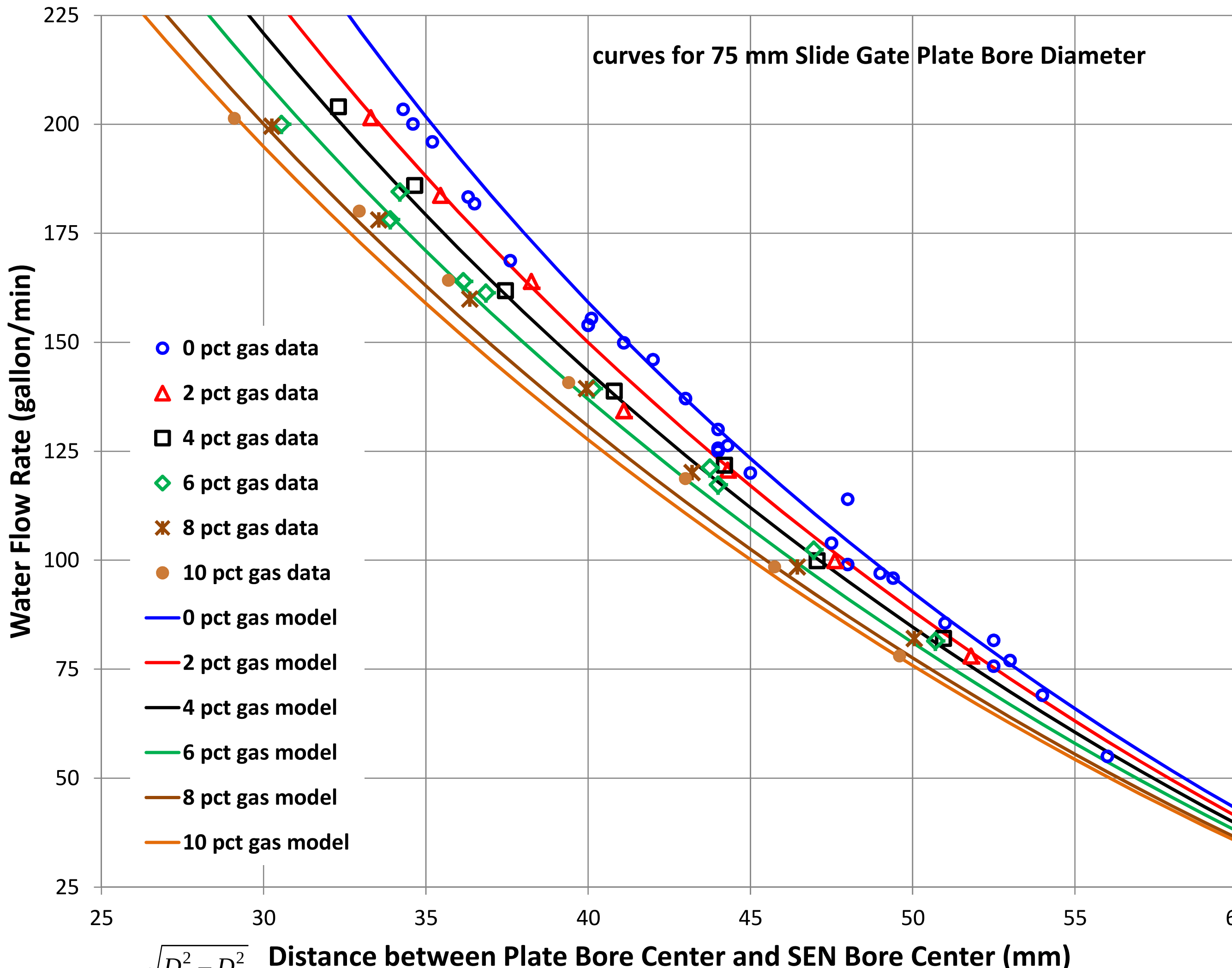
In current study, *C=0* is assumed (no clogging).

Flow Rate Curve – Inlet B.C. (Gate Position vs. Flow Rate)

- **Nice match obtained, analytical SEN flow rate model is validated**
- **Gap area is:**

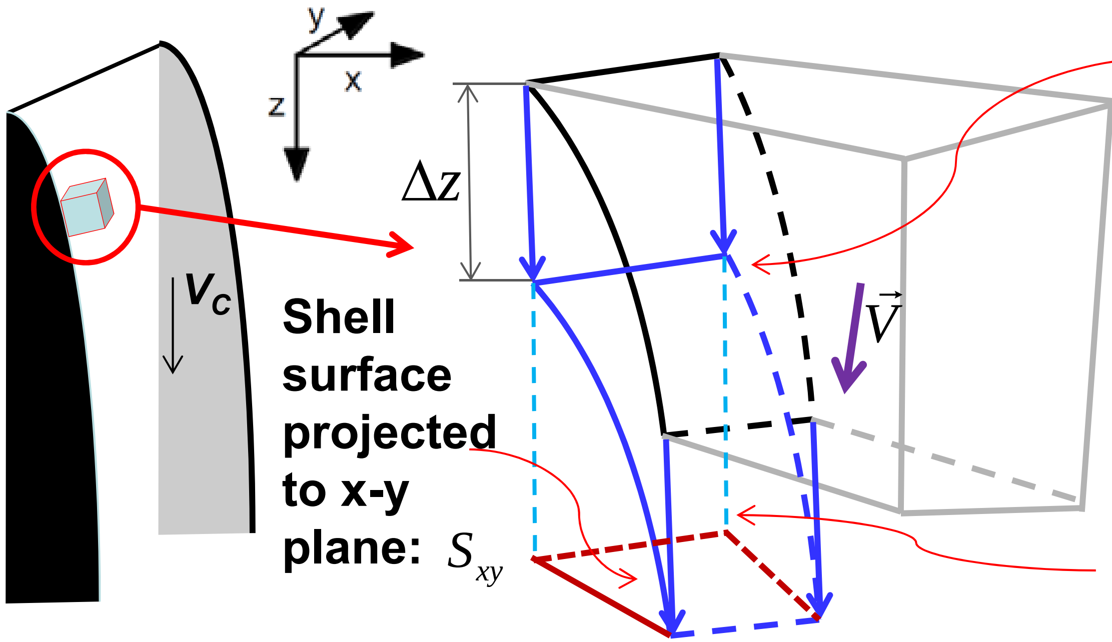


$$h=\frac{D_1D_2}{4D}\sqrt{1-\left(\frac{D_1^2+D_2^2-4D^2}{2D_1D_2}\right)^2}$$



$$A_{GAP}=\frac{D_1^2}{4}\arcsin\left(\frac{2h}{D_1}\right)+\frac{D_2^2}{4}\arcsin\left(\frac{2h}{D_2}\right)-Dh, \quad if \quad D>\frac{\sqrt{D_1^2-D_2^2}}{2}$$

Mass/Momentum Sinks – Shell B.C.



Shell Surface : $z\left(x,y\right)$

Time needed for shell surface to travel this distance: Δt

$$\Delta z = V_C \Delta t$$

Translated Shell Surface :

$$z\left(x,y\right)+\Delta z$$

Volume created by shell surface sweeping:

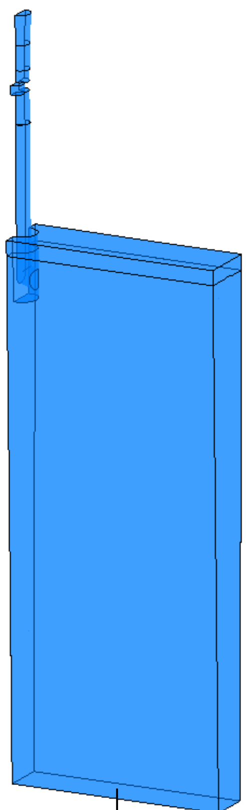
$$\Delta V = \iint_{S_{xy}} \left[\left(z\left(x,y\right)+\Delta z\right)-z\left(x,y\right)\right]dxdy = \Delta z \iint_{S_{xy}} dxdy = \Delta z S_{xy} = V_C \Delta t S_{xy}$$

Corresponding Mass rate: $\Delta m = \rho \Delta V = \rho V_C \Delta t S_{xy} \Rightarrow \boxed{\dot{m} = \rho V_C S_{xy}}$

Corresponding rate of change of Momentum: $\boxed{\dot{\vec{P}} = \dot{m}\vec{V}}$

Pressure Boundary Modification – Domain Outlet B.C.

Q_T: target flow rate
Q_C: calculated flow rate
p_T: target pressure
p_C: calculated (prescribed) pressure at domain outlet



$$\overline{V} = V_{casting} = \frac{Q_T}{WT}$$

- **The proper B.C. at domain outlet should be a specific (target) flow rate, calculated from:**
  - **Slab dimension**
  - **Casting speed**
- **Pressure has to be modified to enforce the target flow rate at each time step, using Bernoulli's equation:**

$$p_C + \frac{\rho V_C^2}{2} = p_T + \frac{\rho V_T^2}{2} \Rightarrow dp = p_T - p_C = \rho \frac{V_T^2 - V_C^2}{2}$$

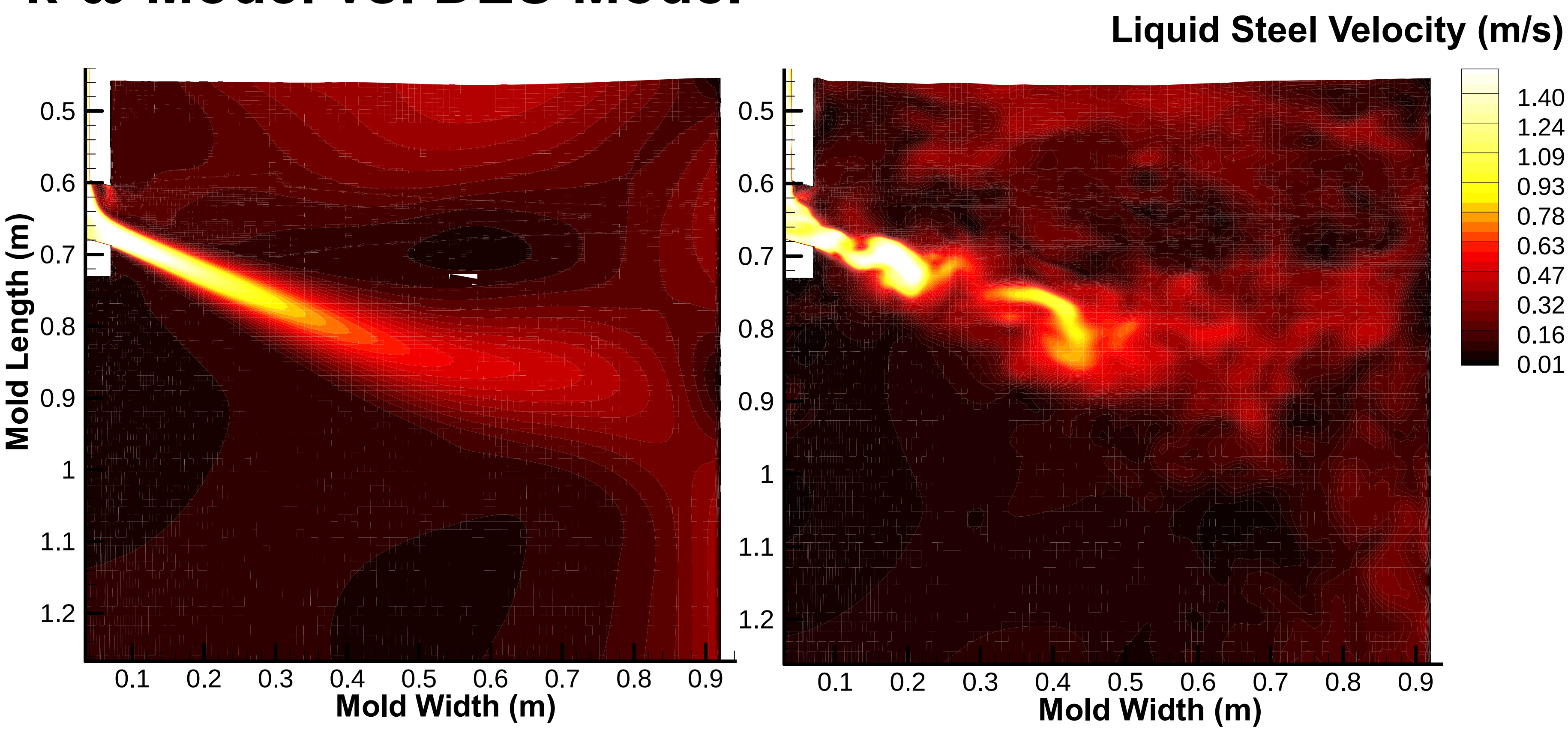
The average pressure correction at domain outlet is:

$$\boxed{d\overline{p} = \rho \frac{\left(\frac{Q_T}{WT}\right)^2 - \left(\frac{Q_C}{WT}\right)^2}{2}}$$

This average pressure correction should be added to the pressure B.C. at domain outlet every iteration

Simulation Results – Quasi-Steady State Solution

k-ω Model vs. DES Model



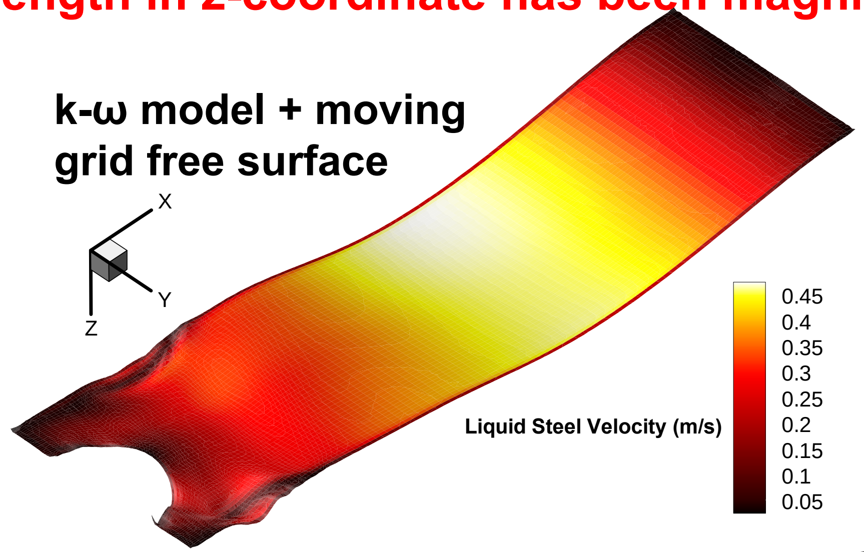
-- velocity distribution from *k-ω* model (diffusive turbulence model used to obtain ensemble averaged solution)

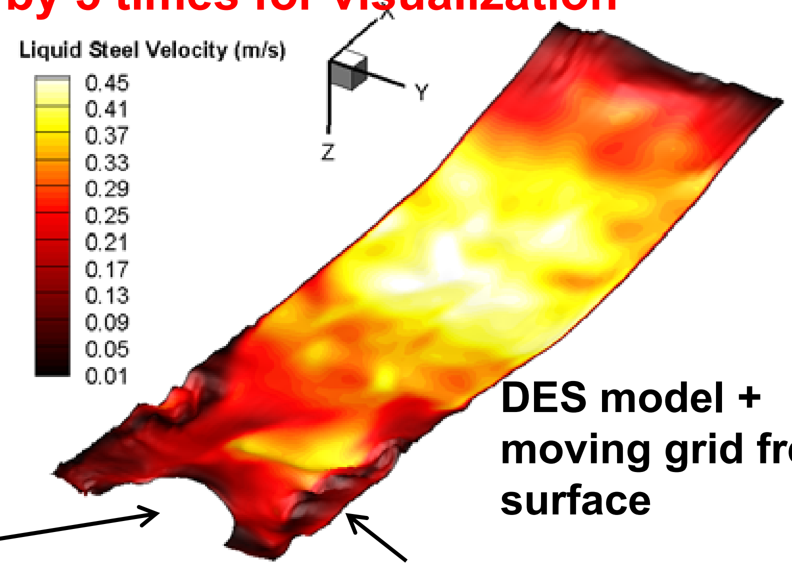
-- velocity distribution from DES model (DES switching between *k-ω* model and LES)

Free Surface Simulation – k-ω vs. DES Model

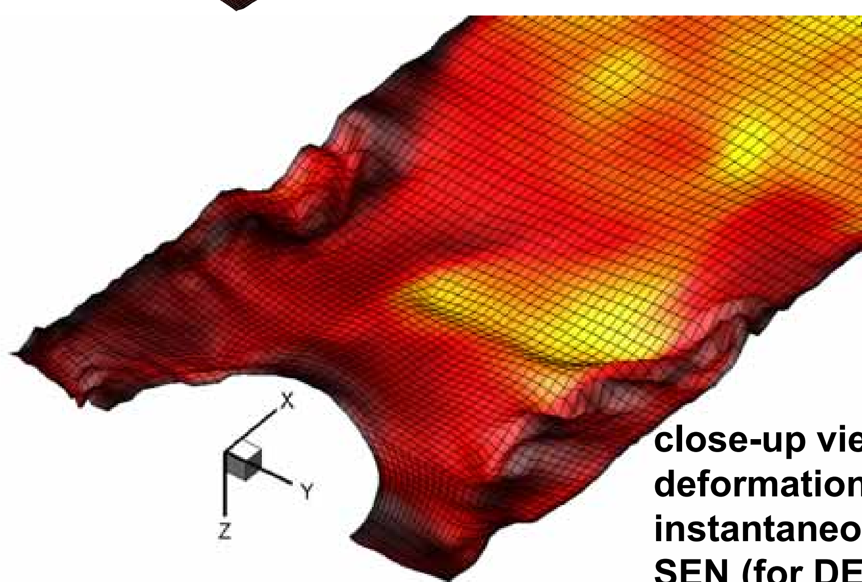
Length in z-coordinate has been magnified by 5 times for visualization

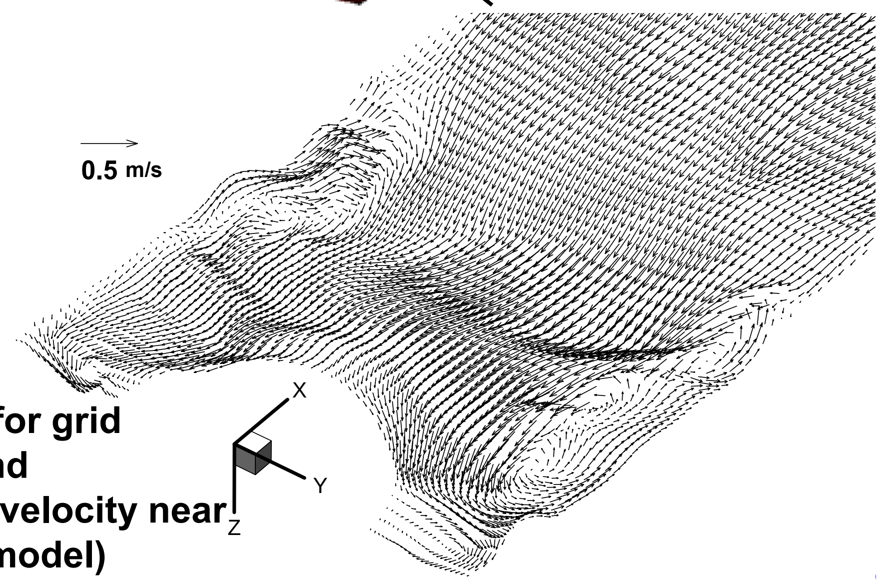
k-ω model + moving grid free surface





DES model + moving grid free surface

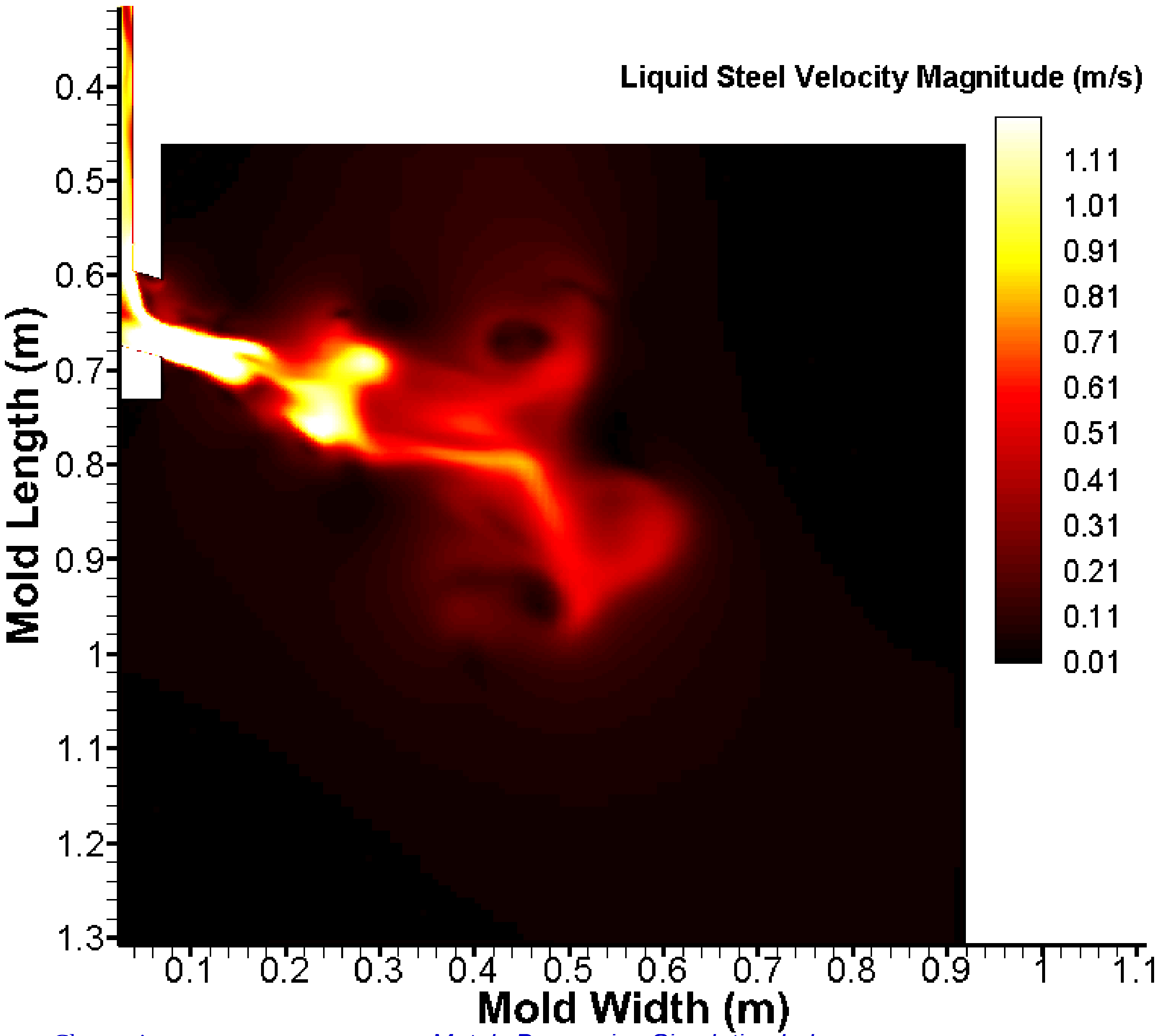




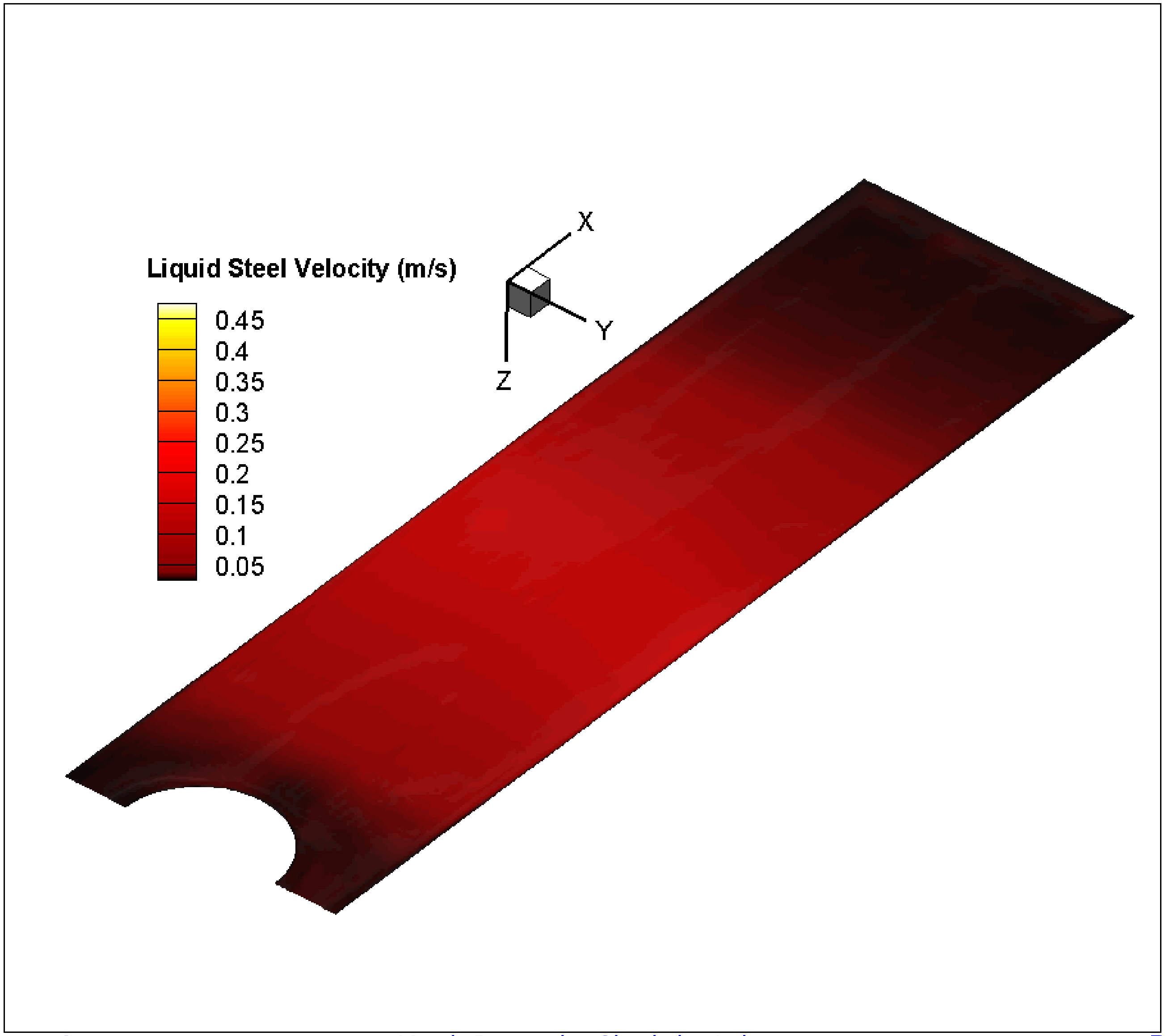
close-up view for grid deformation and instantaneous velocity near SEN (for DES model)

DES Simulated Transient Flow Pattern (quasi-steady state)

- Center plane velocity distribution



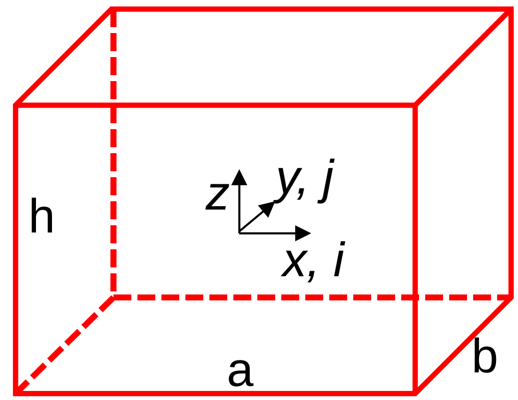
Free Surface Motion (quasi-steady state)



Calculation of Sloshing Frequency in a Rectangular Tank

- **M.C. Kim and S.S. Lee[1] suggested the following equation to calculate the sloshing frequency in a rectangular tank**

$$f_{i,j}^{2} = \frac{g}{4\pi}\sqrt{\left(\frac{i}{a}\right)^2 + \left(\frac{j}{b}\right)^2}\tanh\left[\pi h\sqrt{\left(\frac{i}{a}\right)^2 + \left(\frac{j}{b}\right)^2}\right]$$



In the dithering case, half mold width a is 36.25 inch (0.92 m), and mold thickness b is 10 inch (0.254 m), supposing only mode (i,j) = (1,0) occurs due to SEN blocking effect.

$$\boxed{f_{1,0} = \sqrt{\frac{g}{4\pi a}} = \sqrt{\frac{9.8067}{4\pi \times 0.92}} = 0.92Hz}$$

- **A. Prosperetti[2] derived the analytical solution for 2-D small amplitude waves (sloshing) problem, with the natural frequency as a function of gravity acceleration and wave number *k*:**

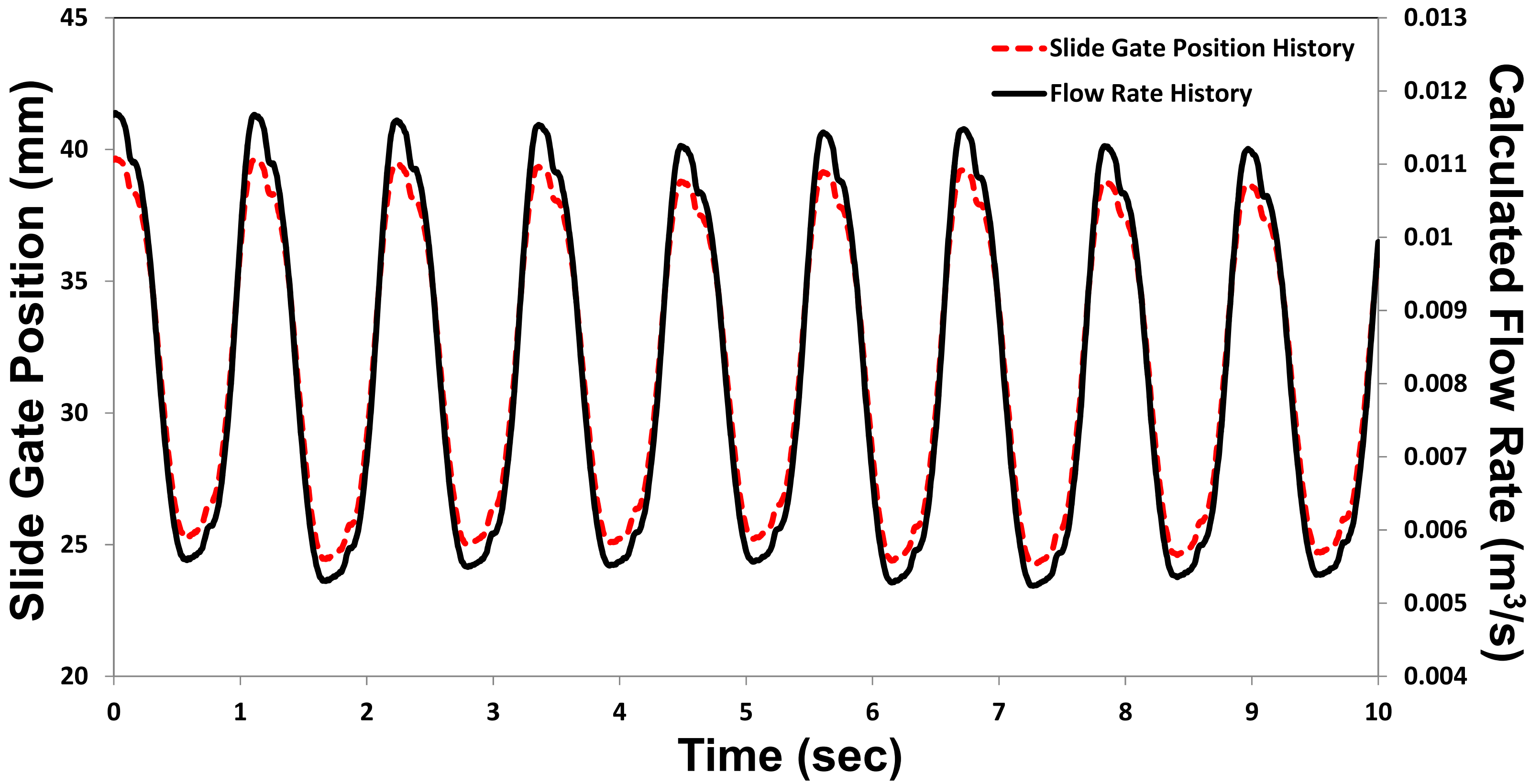
$$\omega_0 = \sqrt{gk} \qquad k = \frac{n\pi}{a}$$

for n = 1, frequency is: $$\boxed{f = \frac{\omega_0}{2\pi} = \sqrt{\frac{g}{4\pi a}} = 0.92Hz}$$

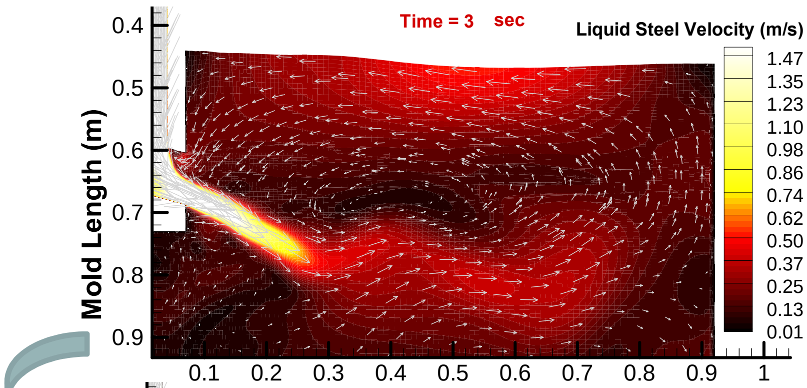
Ref:
[1] M.C. Kim and S.S. Lee, "HYDROELASTIC ANALYSIS OF A RECTANGULAR TANK".
[2] A. Prosperetti, 1981. "Motion of two superposed viscous fluids". Physics of Fluids, 24(7), July, pp. 1217–1223.

Flow Rate Variation during Dithering in Case 3 (Giant Sloshing)

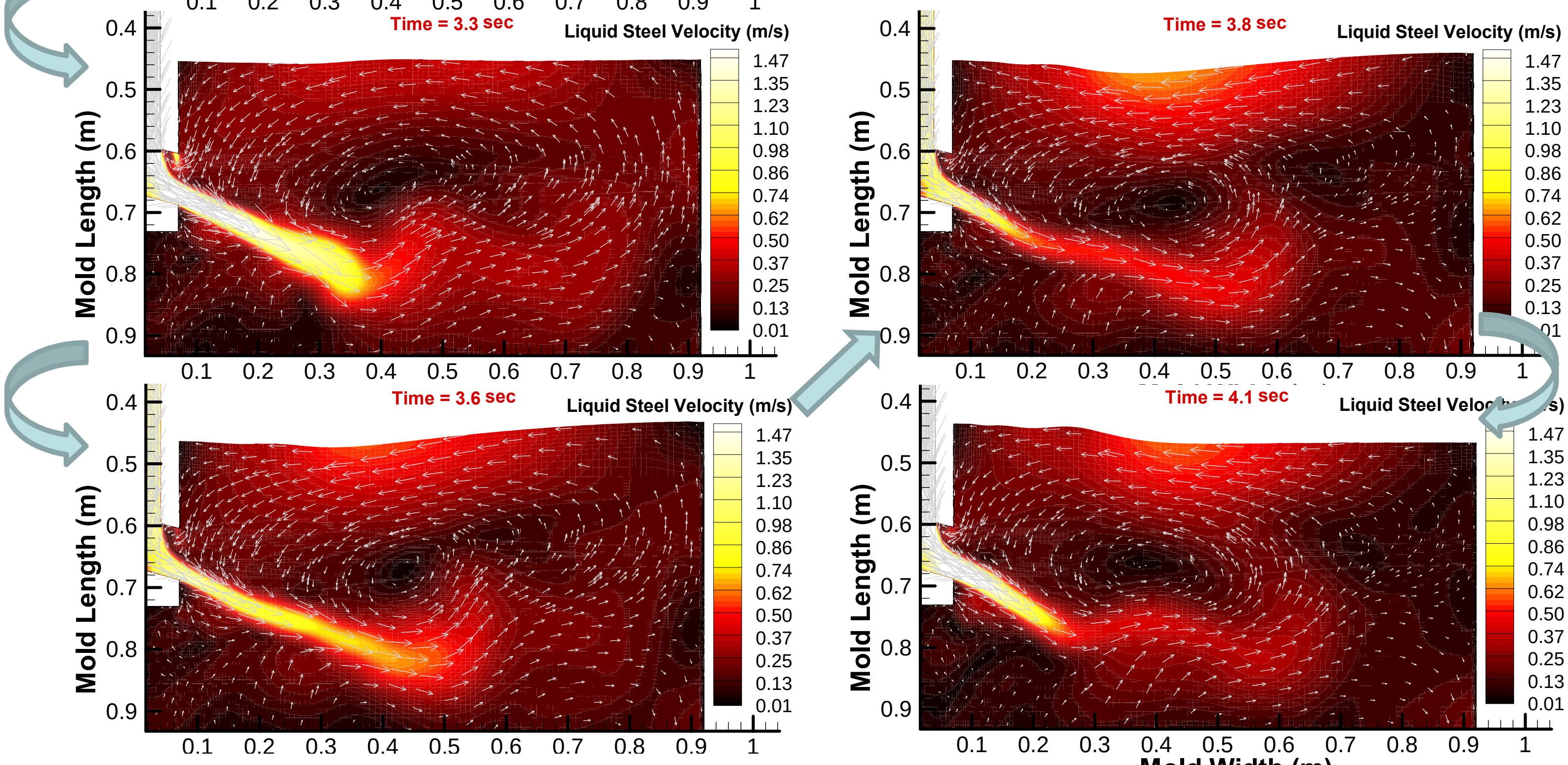
- **Measured slide-gate position is converted into inlet flow rate variations using the gate-position-based model**



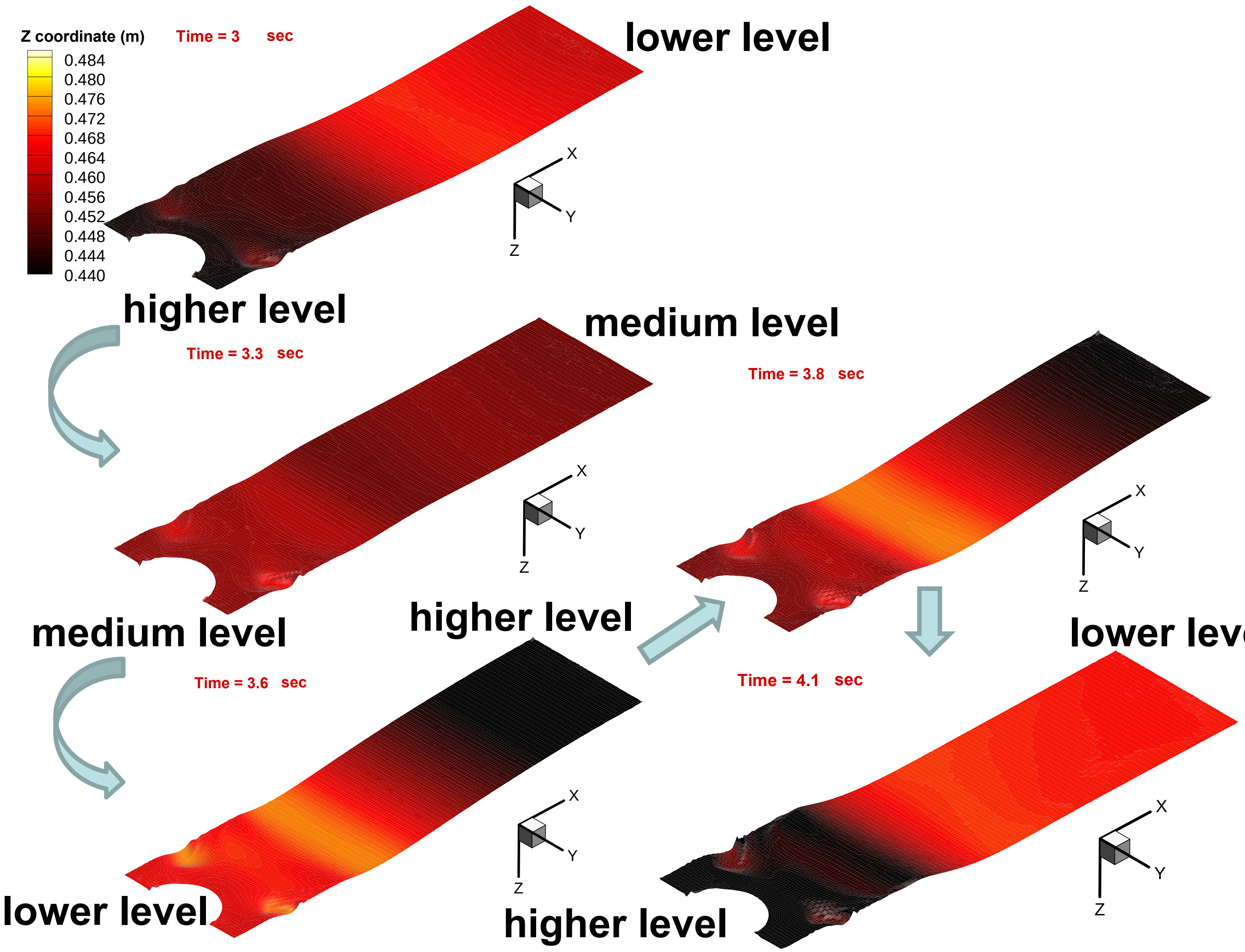
Case 3: Flow Pattern Evolution at Mold Center Plane



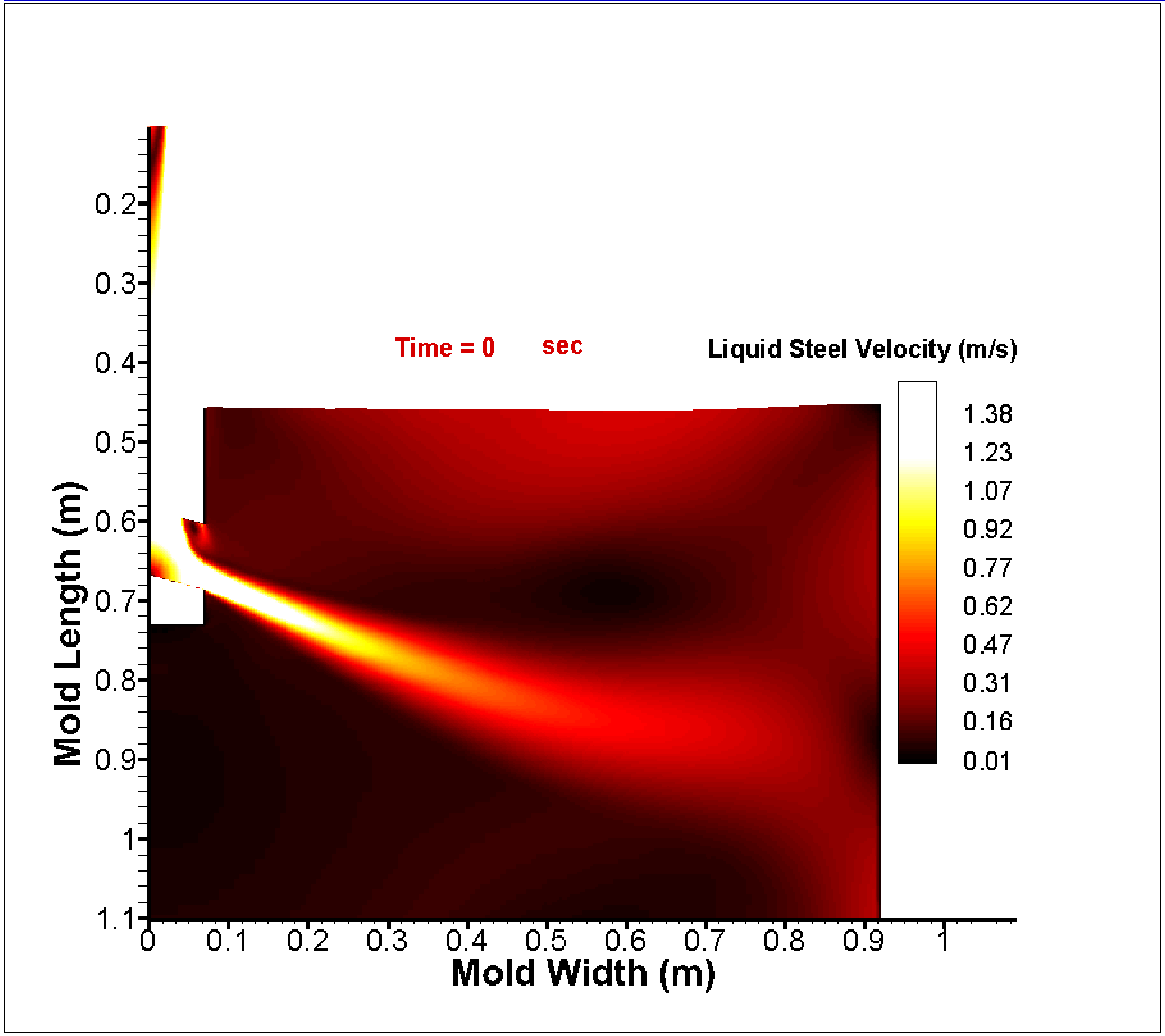
Mold top surface is a swing, and the jet is pushing it periodically…



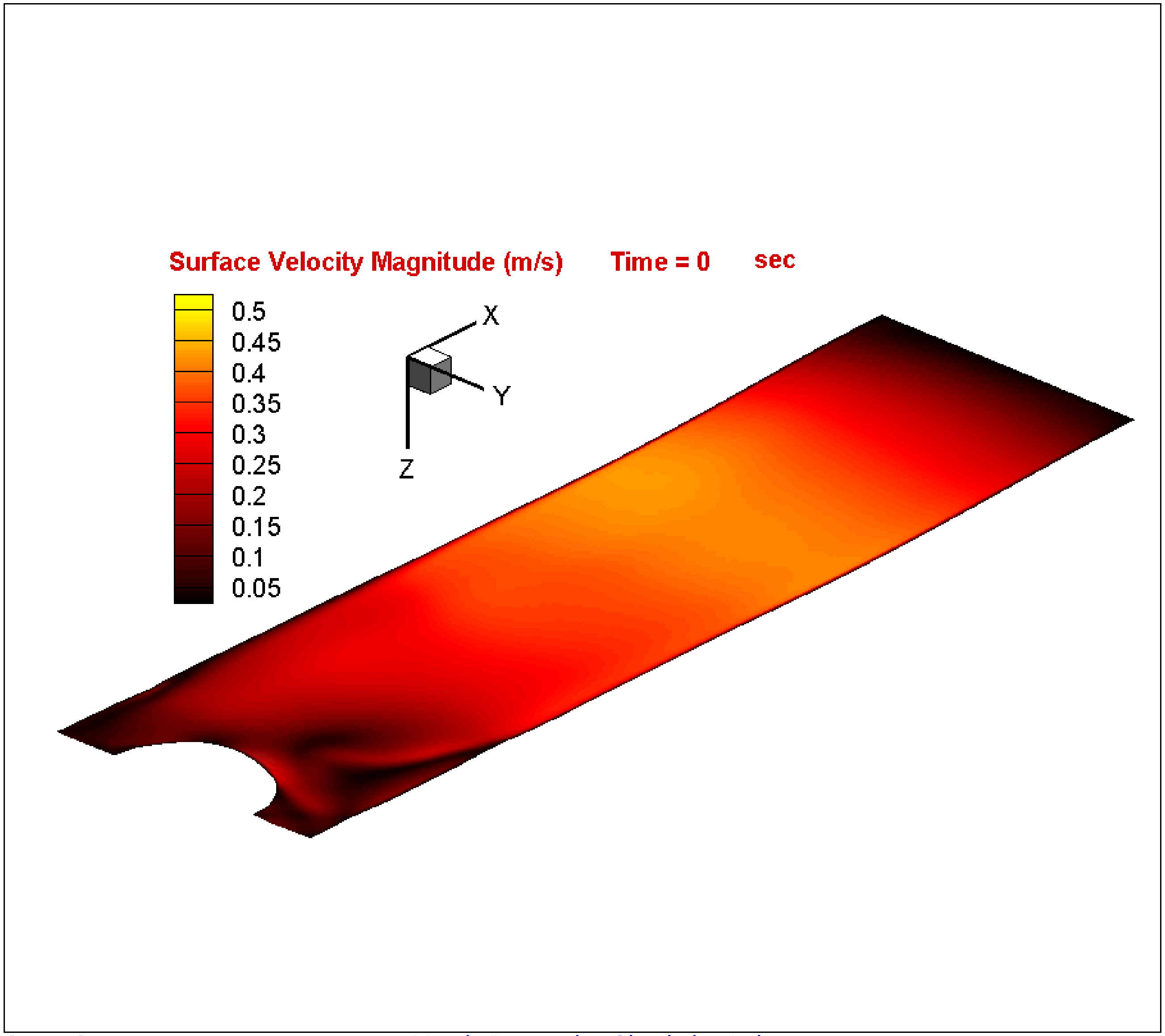
Case 3: Free Surface Behavior



Center Plane Velocity Evolution for Case 3



Free Surface Sloshing for Case 3



Conclusion – Part 2

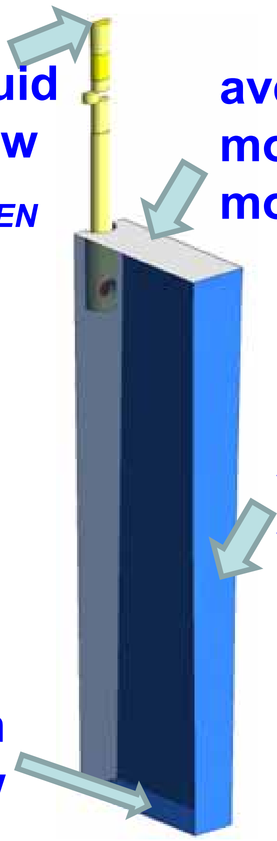
- **Computational models were setup and successfully adopted to investigate transient flow and free surface evolution, with:**
  - **Predicted flow rate at nozzle inlet B.C.**
  - **Mass/momentum sink terms at shell**
  - **Modified pressure B.C. at domain outlet**
- **Sloshing frequency is calculated via analytical solutions and validated via numerical simulation;**
- **The "swing" effect is identified via simulated results as the cause of giant sloshing which was observed to occur when dithering frequency matches with sloshing frequency.**

Part 3

Parametric Study on Mold Level Fluctuations during Dithering

- **Simpler models are needed to predict average mold level fluctuations during dithering process:**
  - **derived from global mass conservation**
  - **with flow rate calculated from gate-position-based model**
- **Effects of the following factors are investigated via parametric study using the simple average mold level model, including:**
  - **dithering stroke**
  - **casting speed**

Derivation of Average Mold Level Equation for Dithering



SEN liquid steel flow rate, Q_{SEN}

average mold level motion, V_l

mass sink at shell interface

domain outflow

$$V_l\left(A_l-\frac{\pi}{4}D_o^2\right)+V_cA_l=Q_{SEN} \qquad A_l=WT$$

$$V_l=\frac{dh}{dt}$$

$$\frac{dh}{dt}=\frac{Q_{SEN}}{\alpha_A A_l}-\frac{V_c}{\alpha_A}$$

$$\alpha_A=1-\frac{\pi D_o^2}{4WT}$$

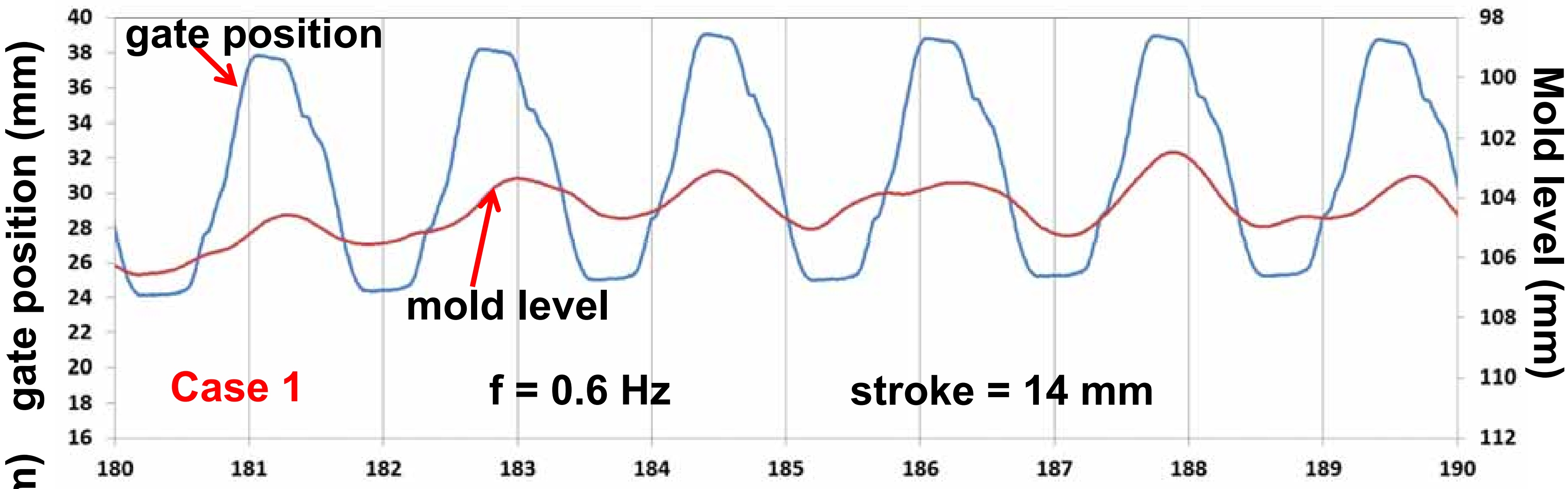
$$h=\int_{t_0}^{t}\left(\frac{Q_{SEN}}{\alpha_A A_l}-\frac{V_c}{\alpha_A}\right)dt'+h_0=\frac{1}{\alpha_A A_l}\int_{t_0}^{t}Q_{SEN}\,dt'-\frac{1}{\alpha_A}V_c\left(t-t_0\right)+h_0$$

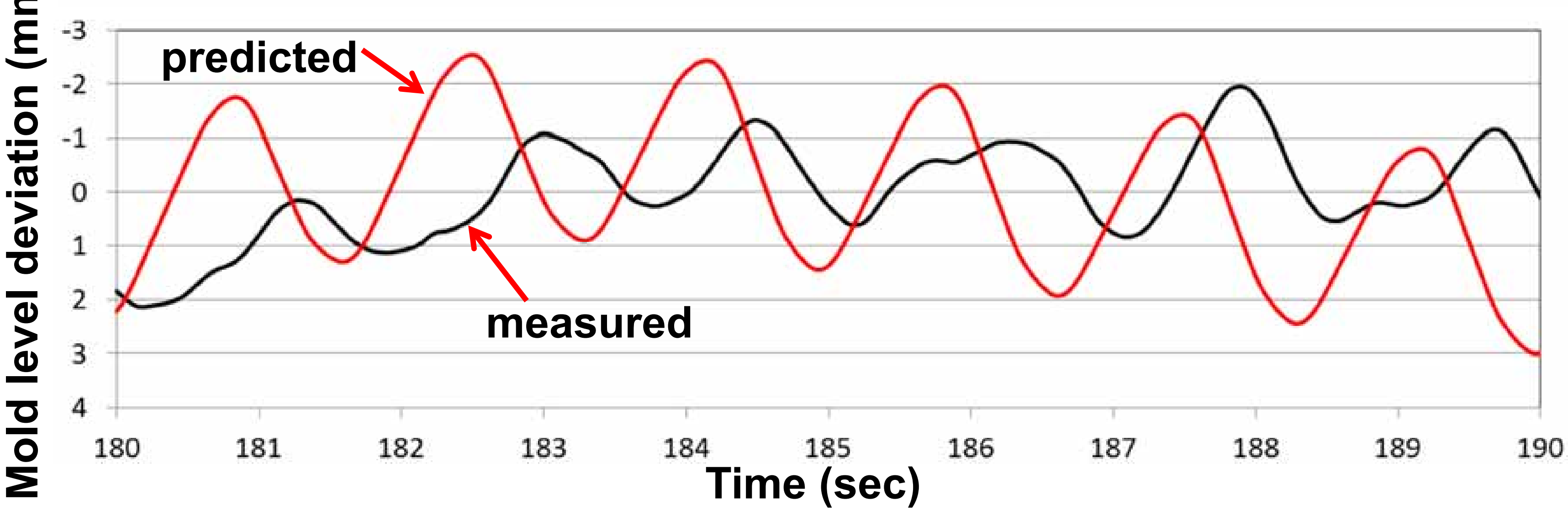
Discretize the equation above in the time domain, resulting in the following form:

$$h_n=\frac{1}{\alpha_A A_l}\sum_{i=0}^{n}Q_{SEN}\left(t_i\right)\Delta t-\frac{1}{\alpha_A}V_c\left(t_n-t_0\right)+h_0$$

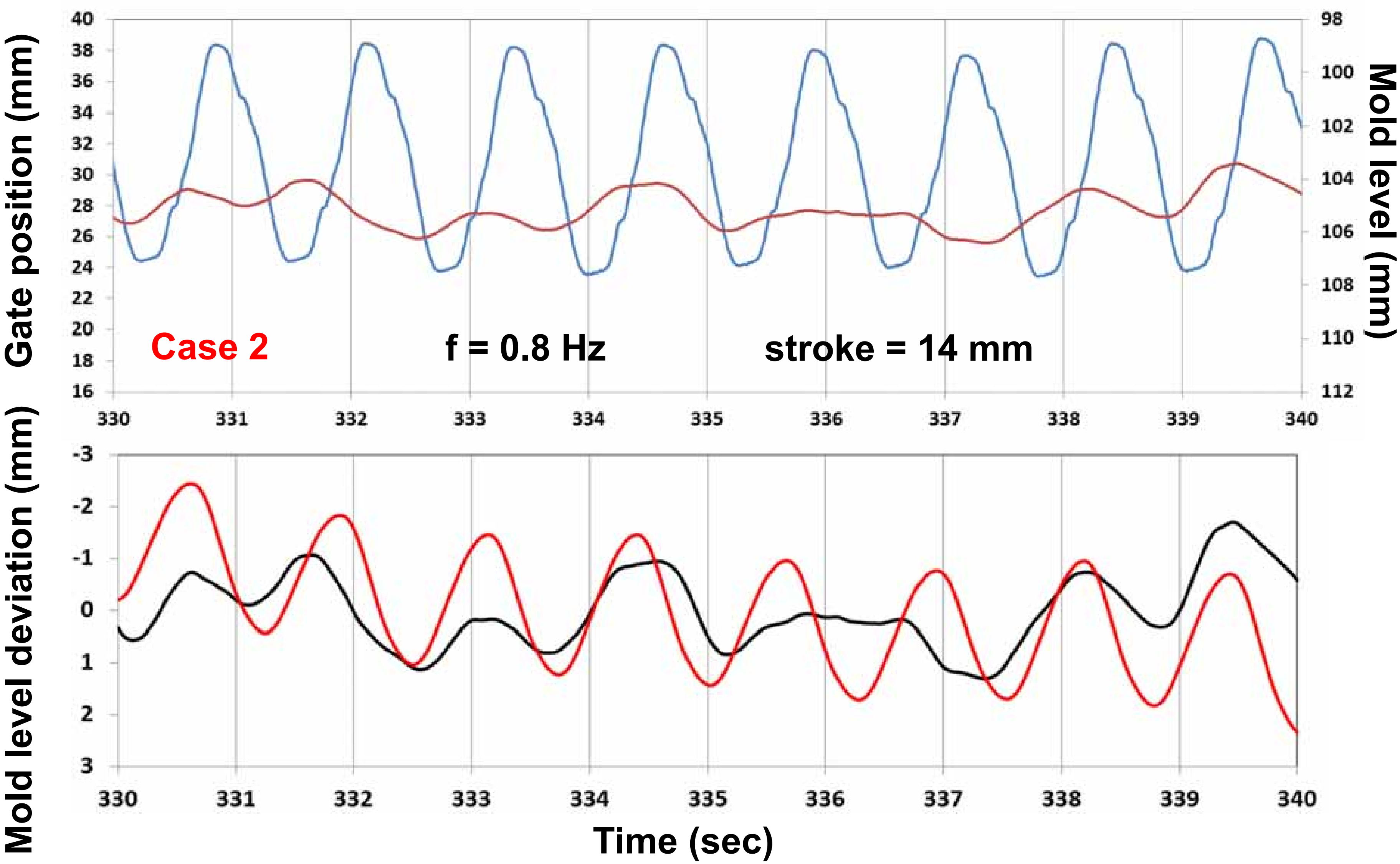
$$Q_{SEN}=A_{eff}\sqrt{\frac{2g\left(H_1+H_2\right)}{\left(\frac{A_{SEN}}{A_{port}}-1\right)^2+f\frac{L_{SEN}}{D_{SEN}}+\left(\frac{1}{\mu}-1\right)^2\left(\frac{A_{SEN}}{A_{GAP}}\right)^2+\left(\frac{A_{SG}}{A_{GAP}}-\frac{A_{GAP}}{A_{SG}}\right)^2\left(\frac{A_{SEN}}{A_{SG}}\right)^2+\left(\frac{A_{SEN}}{2A_{port}}\right)^2}}$$

Predicted and Measured Mold Level – Case 1, 0.6 Hz, 14 mm stroke

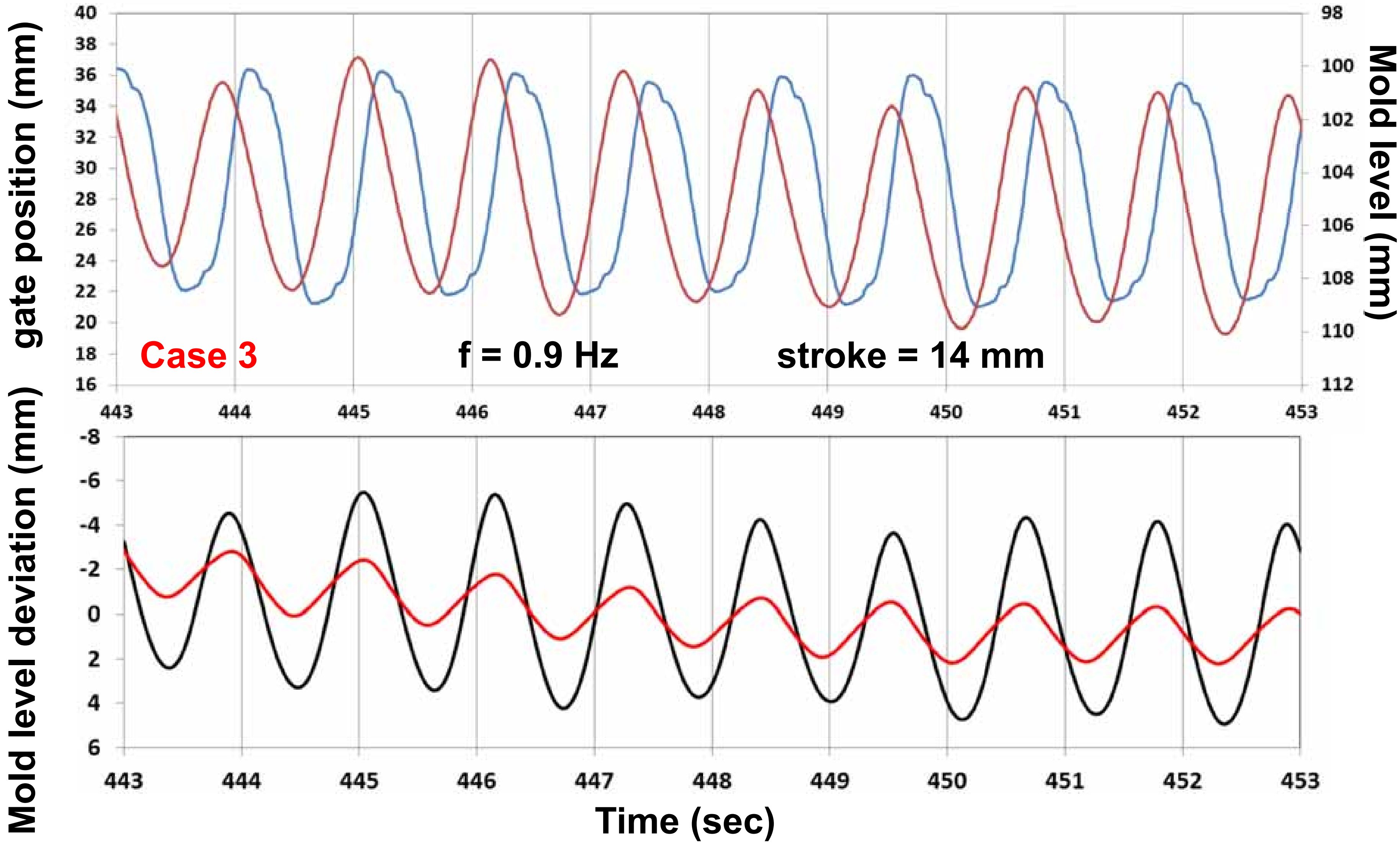




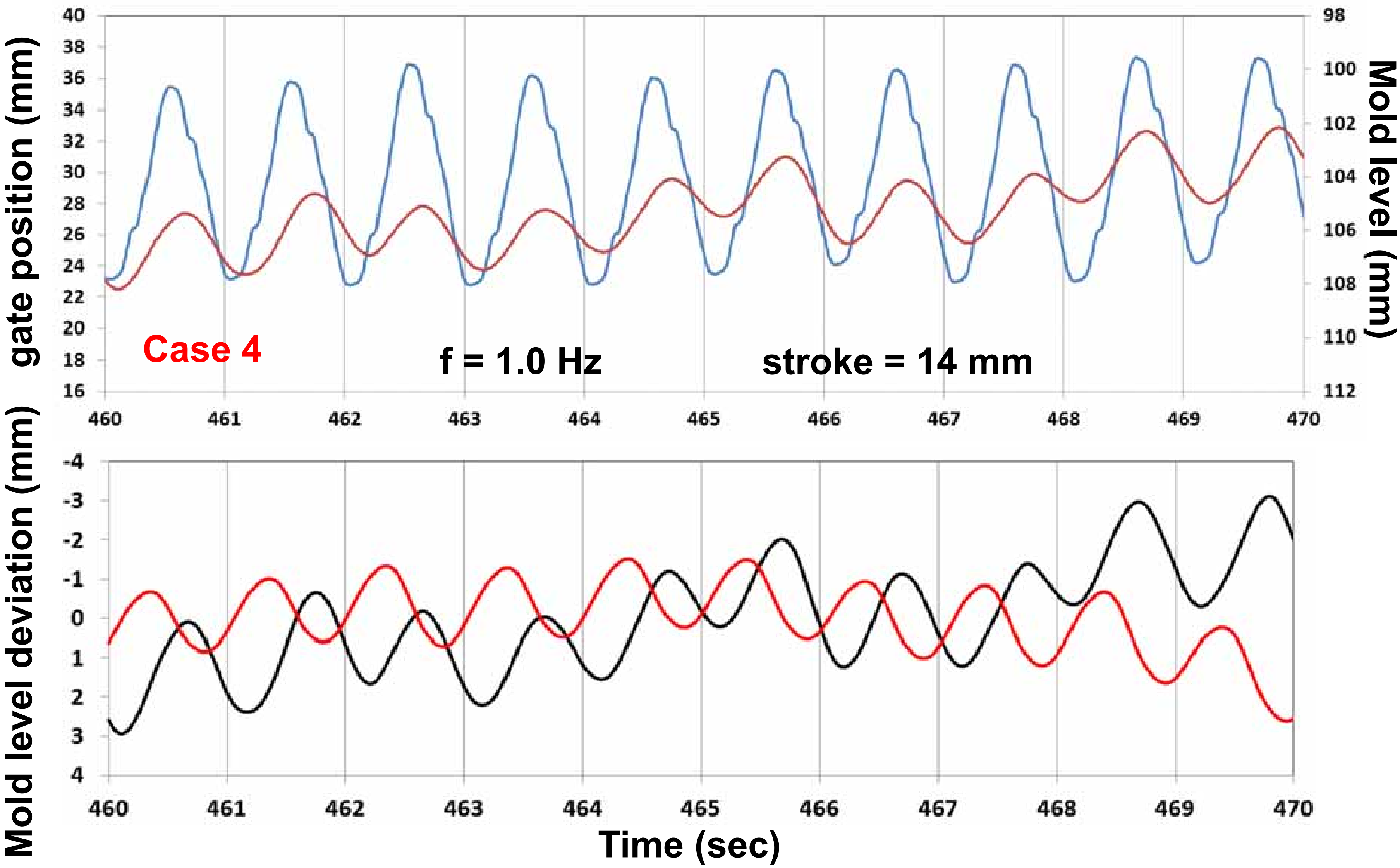
Case 2 – 0.8 Hz, 14 mm stroke



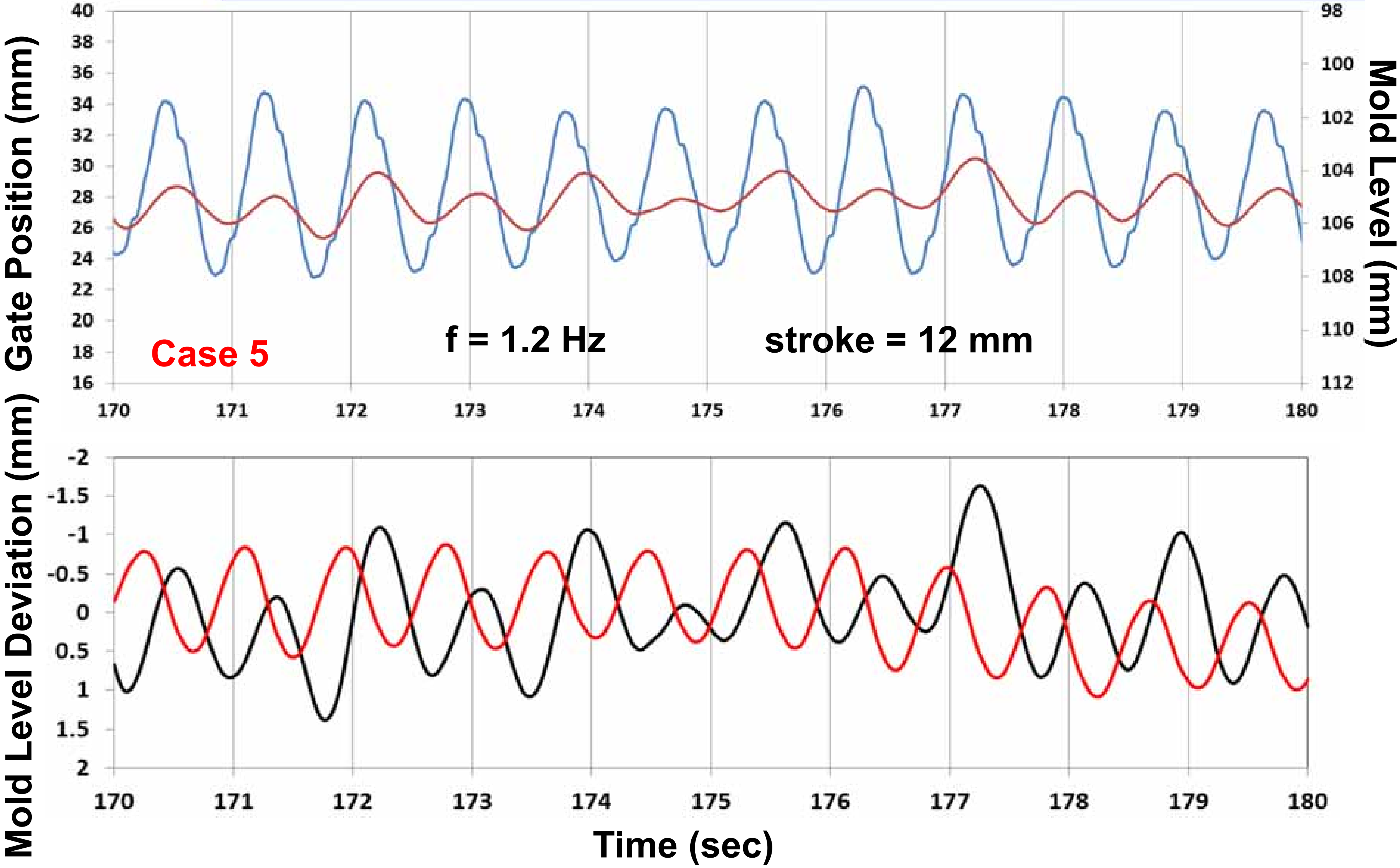
Case 3 – 0.9 Hz, 14 mm stroke



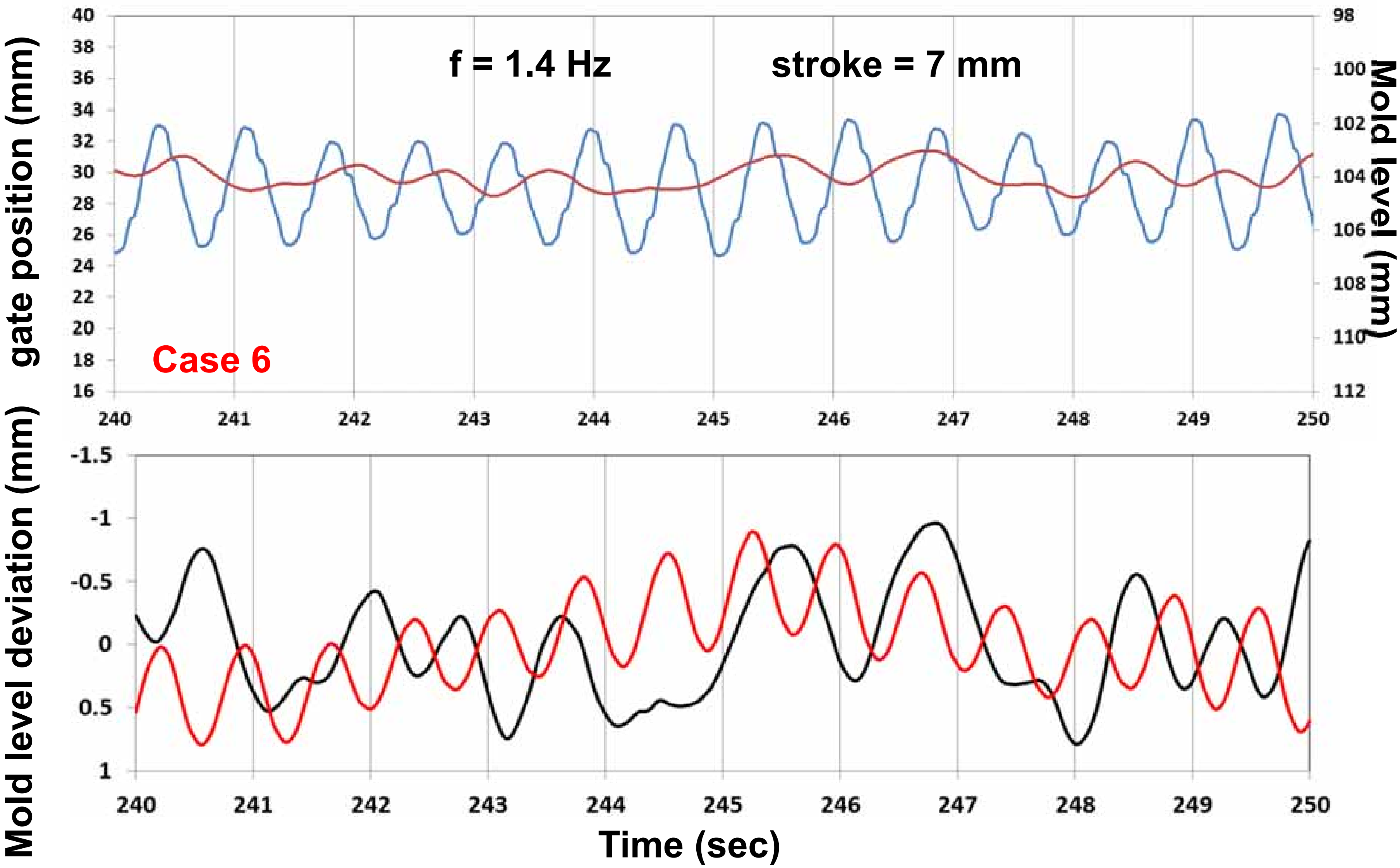
Case 4 – 1.0 Hz, 14 mm stroke



Case 5 – 1.2 Hz, 12 mm stroke



Case 6 – 1.4 Hz, 7 mm stroke



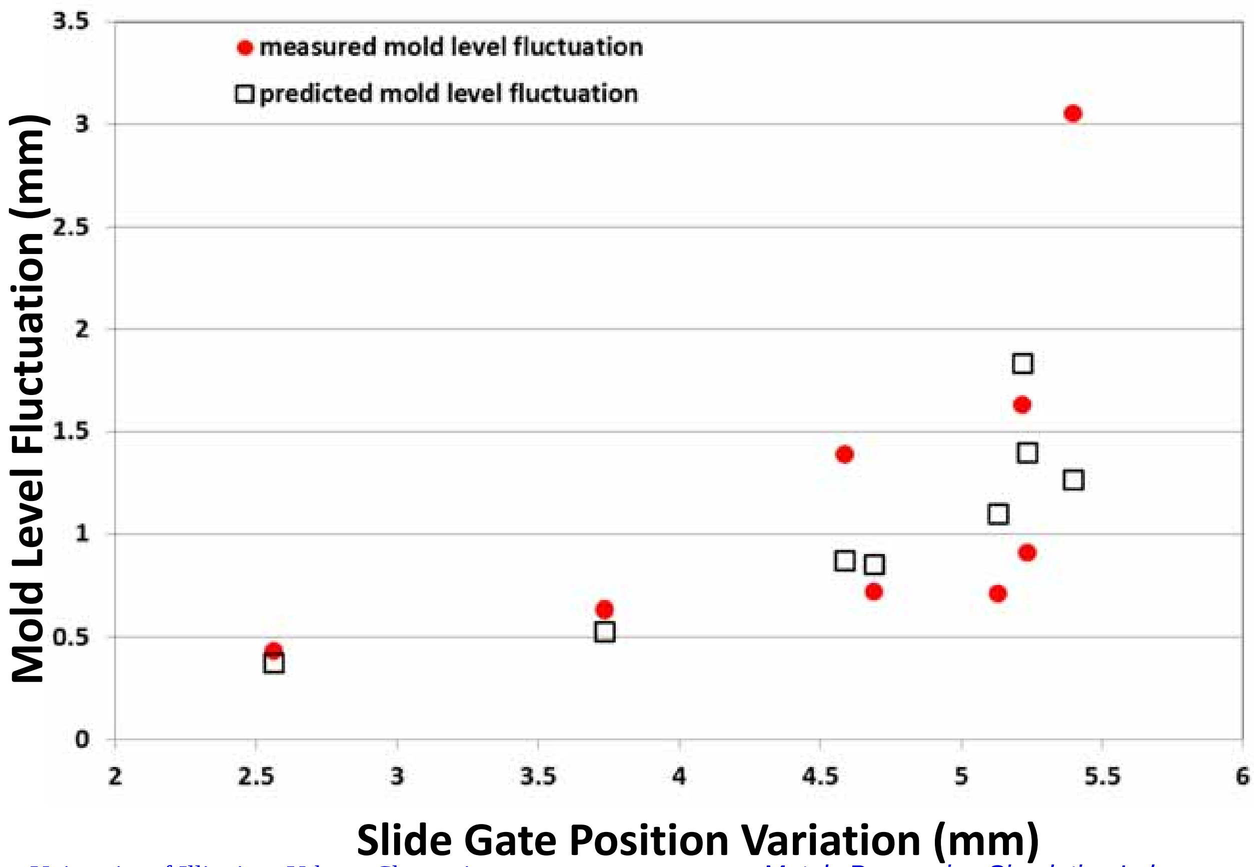
Mold Level Fluctuation

Mold level fluctuation (rms) defined as:

$$h' = h - \bar{h} \qquad \sqrt{\overline{h'^2}} = \sqrt{\frac{\sum_{i=1}^{N}\left(h-\bar{h}\right)^2}{N}}$$

Flow rate variation (rms) defined as:

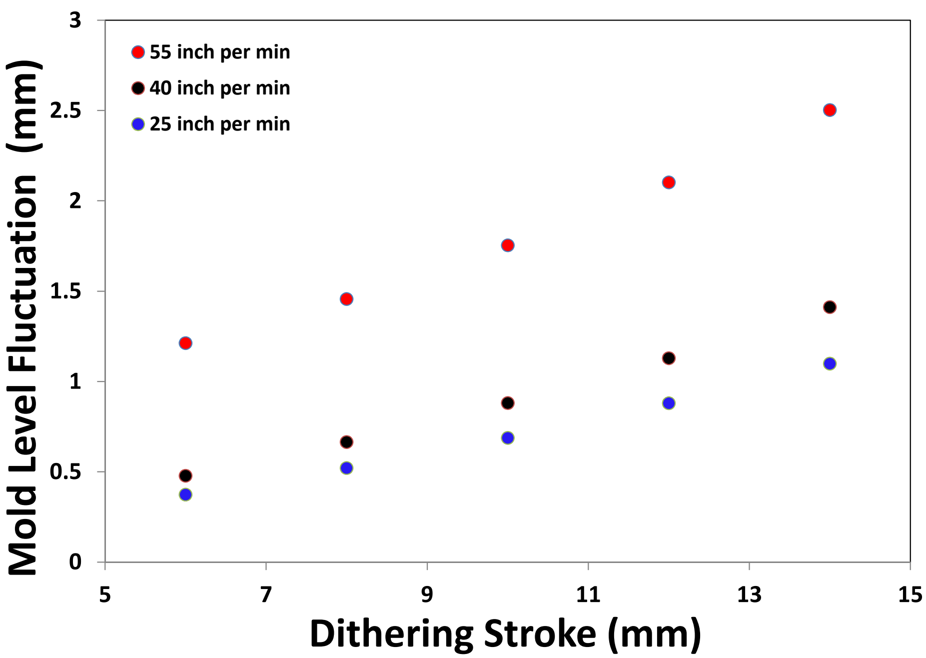
$$d' = d - \bar{d} \qquad \sqrt{\overline{d'^2}} = \sqrt{\frac{\sum_{i=1}^{N}\left(d-\bar{d}\right)^2}{N}}$$

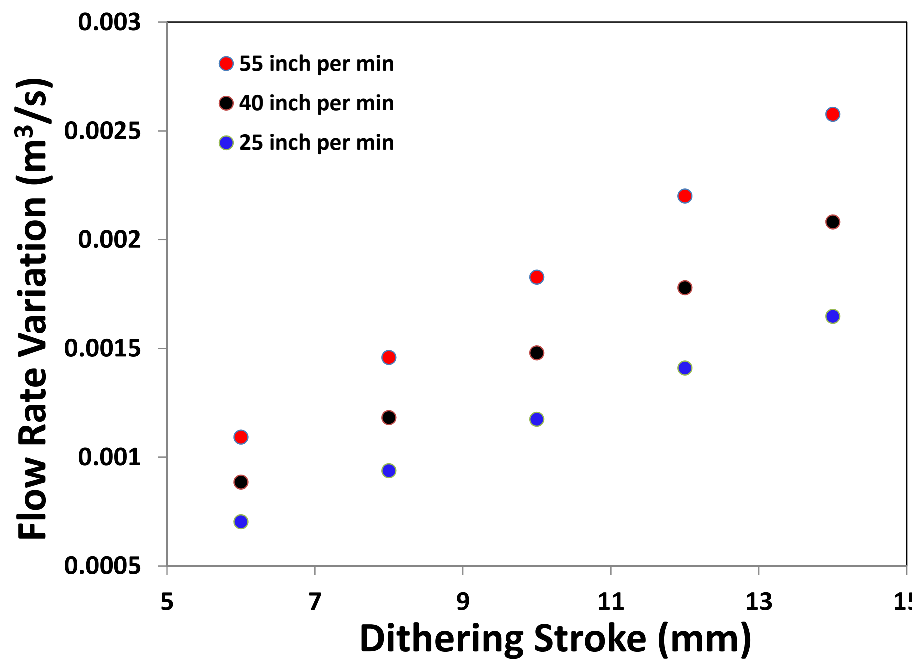


- **Monotonic correlation found between flow rate variation and mold level fluctuations**
- **Mold level fluctuation deviates from the correlation when dithering frequency is very close to sloshing frequency of the mold (0.92 Hz in current case)**

Casting Speed Effect on Level Fluctuations

Tundish level: 58 inches **Mold width: 72.5 inches** **Dither frequency: 0.8 Hz**





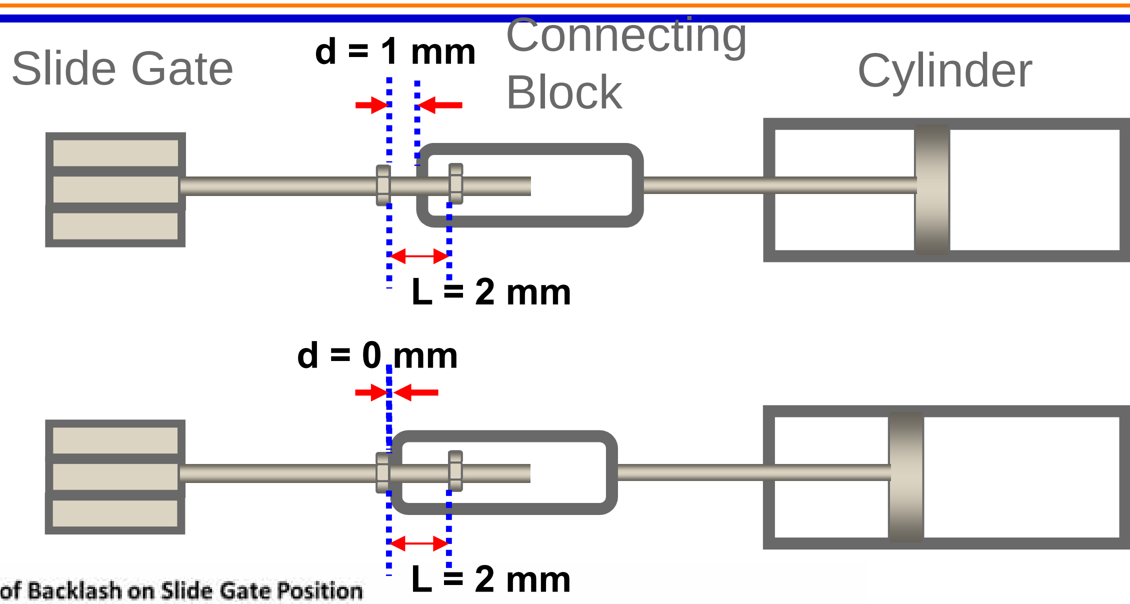
- **Higher speed causes more gate opening, operating in steeper part of flow rate/gate position curve, thus increasing flow-rate and level variations**
- **For each casting speed, both flow rate variation and mold level fluctuation change almost linearly with dithering stroke (not at sloshing frequency)**

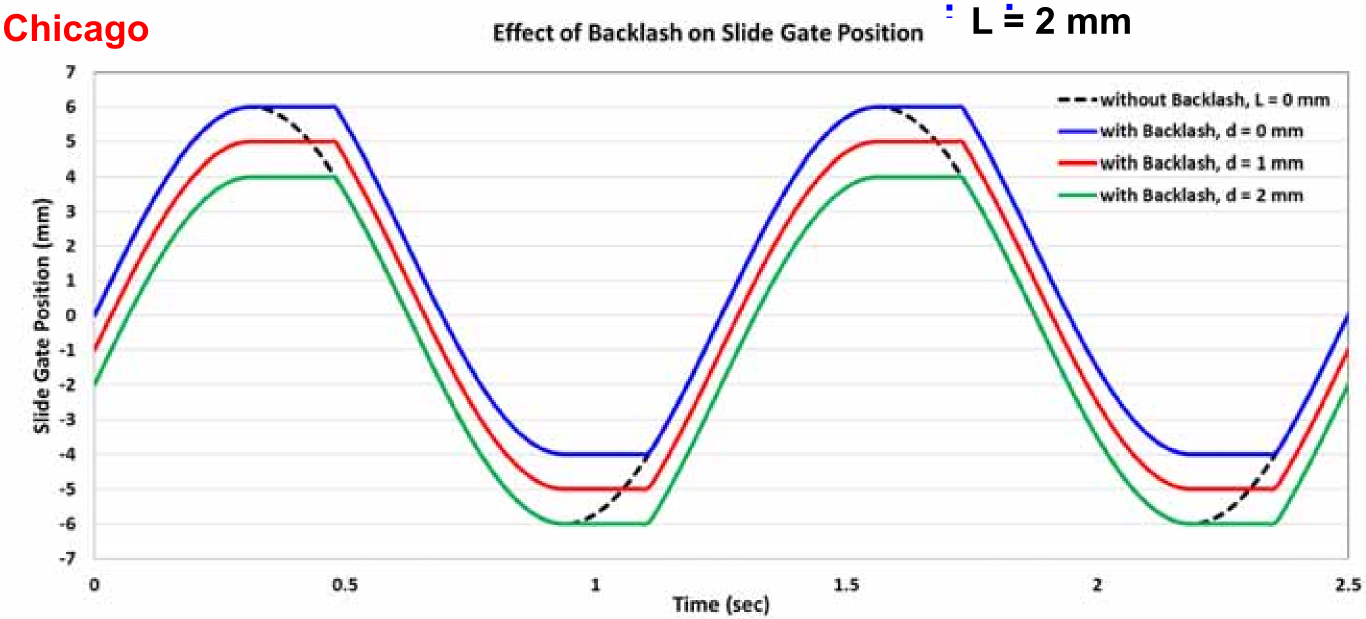
Backlash Effect on Slide Gate Position

Initial position of the cylinder relative to the connecting block is crucial to backlash analysis,

d and L are the two important parameters

Schematic of backlash from ArcelorMittal Research Center at East Chicago





Conclusions – Part 3

- **Dithering frequency does not affect mold level fluctuations unless it is very close to the sloshing frequency of the mold (less than ±0.1 Hz);**
- **Predicted mold level fluctuation matches reasonably well with measurements, which proves the potential use of the simple analytical model during dithering;**
- **Flow rate variation during dithering is approximately linearly correlated with dithering stroke;**
- **Increasing casting speed or tundish level increases mold level fluctuation by opening the slide-gate wider, which creates more flow rate variation during dithering.**

Conclusions – Part 3 (cont.)

- **Effects of backlash on mold level fluctuation is complicated:**
  - both "actual" slide-gate position and dithering stroke are affected by backlash;
  - Initial position of slide-gate, together with the initial relative position of connecting block and cylinder determines the actual flow rate and flow rate variation during dithering;
  - Slide-gate dithering from a steady gate position for a casting speed will cause mold level to rise, thus the average position of the slide-gate dithering should be calibrated taking into account both local slope of flow rate curve and backlash effect.

Future Work

- **Multiphase flow modeling**
  - CU-FLOW GPU code development with Eulerian-Lagrangian approach to model two phase bubbly flows in CC process;
  - model validation using water model PIV experiment
- **More parametric study cases with:**
  - the effect of mold width on flow rate variation and mold level fluctuation
  - backlash effect on flow rate during dithering

Acknowledgements

- **Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Tata Steel, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech, Posco, SSAB, ANSYS-Fluent)**
- **Hongbin Yin, Tathagata Bhattacharya, Love Kalra, Kai Zheng, William Umlauf and Aloka Dasgupta in ArcelorMittal East Chicago research center**
- **Jean-Francois Domgin in ArcelorMittal Maizières France and Joydeep Sengupta in ArcelorMittal Dofasco in Canada**
- **Students in Metals Processing Simualtion Lab in UIUC**