CCC Annual Report

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Transient Thermo-fluid Model of Meniscus Behavior and Oscillation Mark Formation

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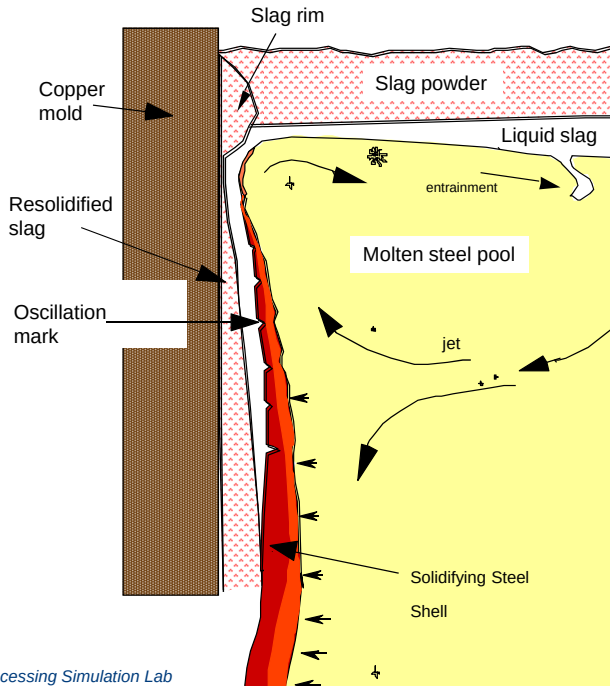
Background

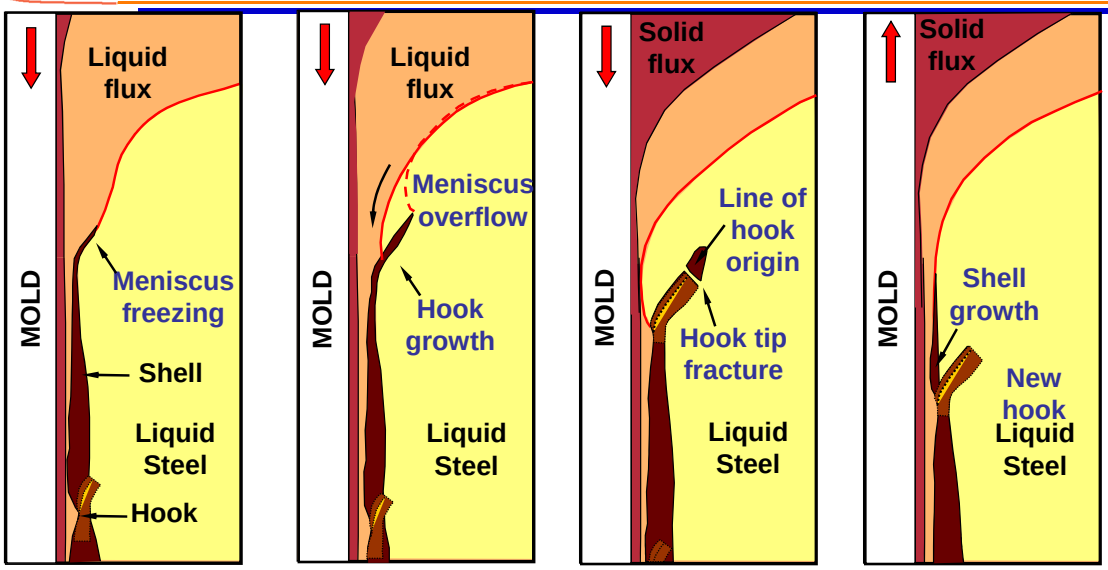
- Meniscus region controls many casting defects, such as:
  - Level fluctuations
  - Slag entrapment
  - Deep oscillation mark
- Many coupled phenomena occur,
  - melting powder,
  - oscillating mold,
  - steel flow with superheat,
  - re-solidified slag rim hitting meniscus and pushing liquid slag into gap
  - heat transfer through the gap and top slag layer,
  - meniscus freezing,
  - overflow
  - Steel shell moving down



Objectives

- Develop a transient thermo-fluid model of meniscus behavior and shell solidification
- Investigate mechanism of oscillation mark formation
- Predict during mold oscillation
  - Transient flow behavior of slag in meniscus region
  - Transient heat flux, temperature profile near meniscus
  - Strand profile, shell thickness
  - Slag gap thickness, oscillation mark depth

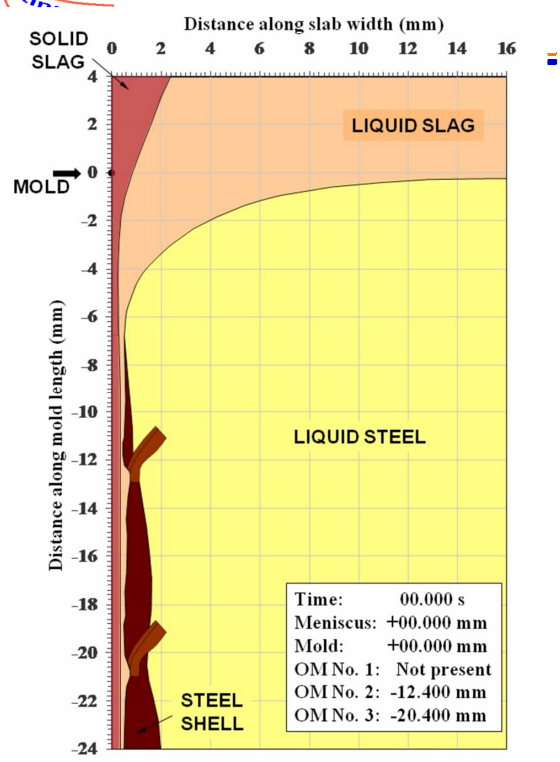
Mechanisms of Hook & OM Formation – Overflow with hook



Other mechanisms:
"mini-sticker";
bending;
overflow without hook
thermal distortion

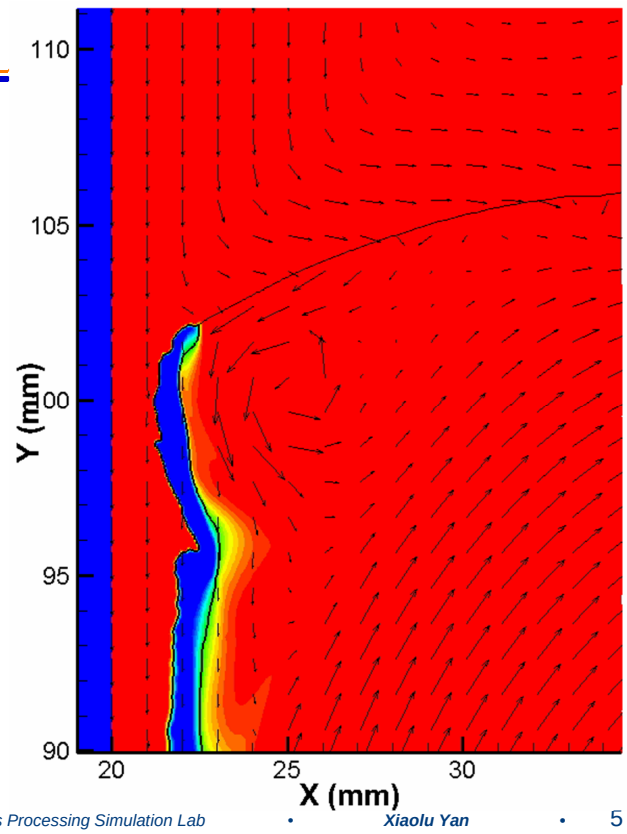
J. Sengupta, H. Shin, BG Thomas, et al, Met Trans B, 2006

Hook – Overflow Animation



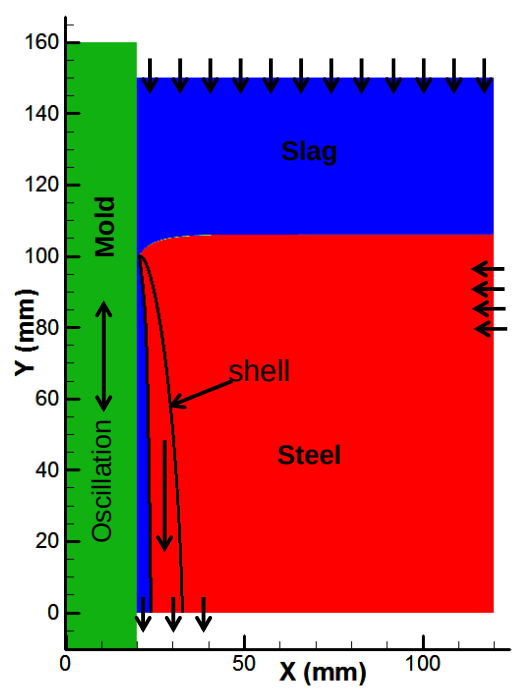
K. Thomas and BG Thomas, UIUC, 2010

Simulation result in current work



Domain & modelling method

- 2D simulation of a center slice through mold, gap, shell and liquid in the meniscus region
- K-ω SST turbulent CFD model to allow both turbulent flow in steel and laminar flow in slag and boundary layer
- Transient heat transfer
- Solidification of slag rim by increased specific heat and viscosity (temperature dependent functions)
- Solidification of steel by extracting latent heat and increasing viscosity and fixing shell velocity to casting speed
- VOF (volume of fluid) method to separate slag & steel phases



Equations

- $k-\omega\ SST\ Model$:

$$\begin{cases} \frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\Gamma_k\frac{\partial k}{\partial x_j}\right)+G_\omega-Y_\omega+S_\omega \\ \frac{\partial}{\partial t}(\rho \omega)+\frac{\partial}{\partial x_i}(\rho \omega u_i)=\frac{\partial}{\partial x_j}\left(\Gamma_k\frac{\partial \omega}{\partial x_j}\right)+G_\omega-Y_\omega+S_\omega \end{cases}$$

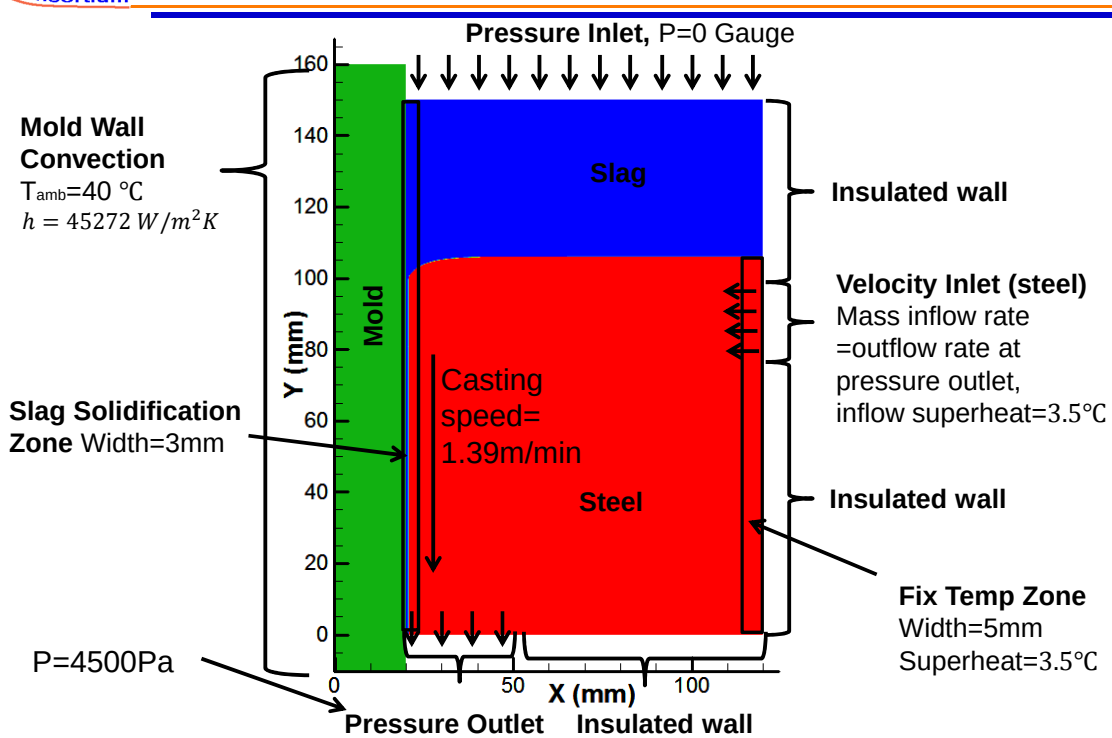
- *VOF method:*

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(\alpha_q\rho_q)+\nabla\cdot(\alpha_q\rho_q\overrightarrow{v_q})=S_{\alpha_q}+\sum_{p=1}^{n}(\dot{m}_{pq}-\dot{m}_{qp})\right]$$

- *Solidification:*

$$\beta=\frac{T-T_{sol}}{T_{liq}-T_{sol}}$$

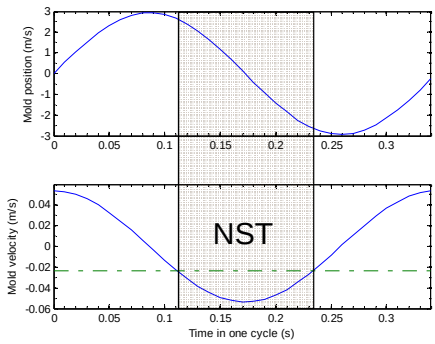
Boundary conditions



Material property & casting condition

Casting condition

	Unit	value
Stroke	mm	5.89
Oscillation frequency	Hz	2.9
Casting speed	m/min	1.39
Negative strip time	s	0.12
Theoretical pitch	mm	8.01



Steel property (ULC)

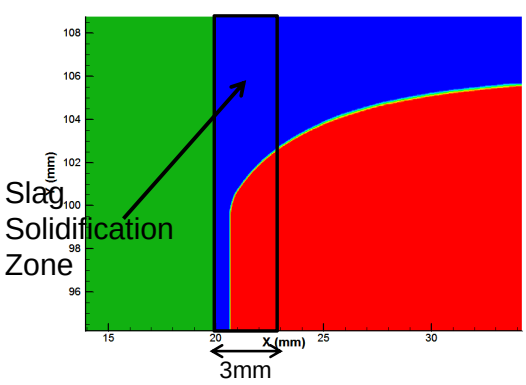
	Unit	value
Density	Kg/m^3	7000
Specific heat	$J/kg \cdot K$	700
Conductivity	$W/m \cdot K$	30
Latent heat	J/kg	2.72×10^5
Solidus temperature	℃	1528.85
Liquidus temperature	℃	1529.85

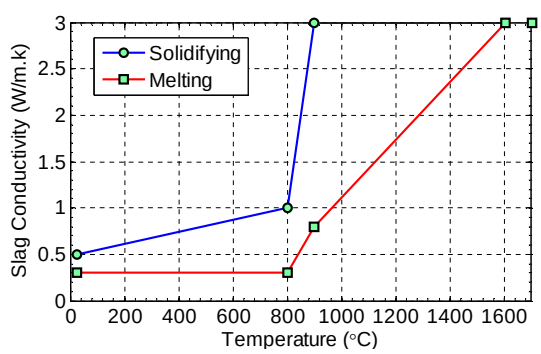
Slag property

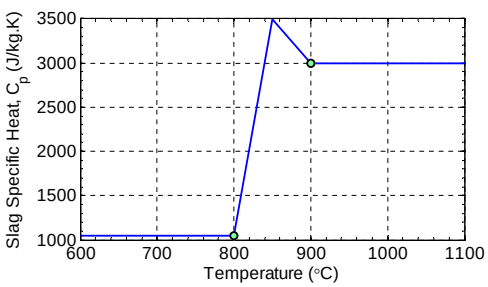
	Unit	value
Density	Kg/m^3	2500

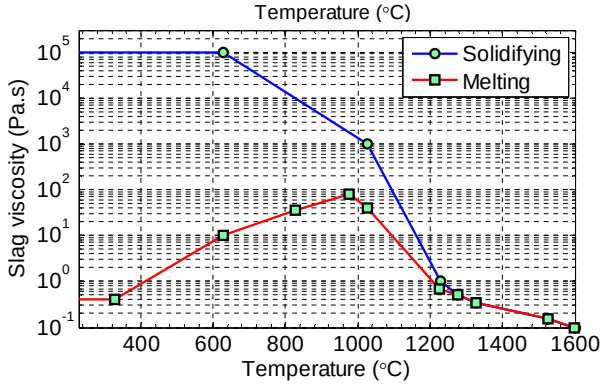
Slag-steel interfacial tension coefficient:
$\gamma(N/m) = 1.3 + 8.38 \times 10^{-4} \times (1803 - T(K))$

Slag properties – spatial and temperature variation









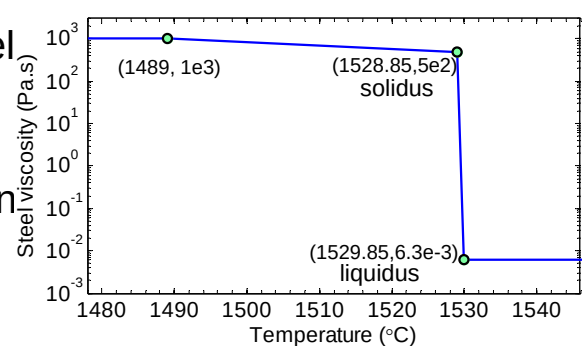
Fix solid steel shell velocity

- ADJUST UDF is used to fix steel shell velocity. It changes its value to casting speed at the beginning of each calculation iteration.
- When a cell satisfies:
  - Temperature <T_{sol}-0.1K
  - VOF fraction of steel > 0.8

  Fix: $\begin{cases} V_x = 0 \\ V_y = 1.39m/min = casting\ speed \end{cases}$
- Case 1: only adjust bottom of shell (y < 88mm)
- Case 2: applied to whole domain (including shell tip in meniscus region)

Steel shell viscosity

- Plasticity dominates solid steel mechanical behavior near solidus temperature
- Stress depends more on strain rate than strain
- Viscosity is appropriate to describe its mechanical behavior
- Current model only uses viscosity ~$10^3 Pa \cdot s$ to avoid convergence issues with the real viscosity (that is 10^4 ×higher)



- Case 1: Only has $10^3 Pa \cdot s$ viscosity in meniscus region
- Case 2: In addition, uses Adjust function to fix velocity, effectively making viscosity infinite

Steel shell viscosity - theory

Constitutive equations for delta-ferrite

$$\begin{cases} \dot{\bar{\epsilon}}\,(1/s) = 0.1{F_\delta}^n \\ F_\delta = \dfrac{\bar{\sigma}\,(Mpa)}{f_c \cdot \left(\dfrac{T(K)}{300}\right)^{-5.52} \cdot (1+1000\bar{\epsilon})^m} \\ f_c = 13678 \times (pct\ C)^{-0.0556} \\ n = (1.617 \times 10^{-4} \times T(K) - 0.06166)^{-1} \\ m = -9.4156 \times 10^{-5} \times T(K) + 0.349501 \end{cases} \Rightarrow \begin{cases} \mu = \dfrac{\tau_{xy}}{\dot{\epsilon}_{xy}} = \dfrac{2}{3} f_c \cdot \left(\dfrac{T(K)}{300}\right)^{-5.52} \dfrac{1}{\dot{\bar{\epsilon}}} (10\dot{\bar{\epsilon}})^{\frac{1}{n}} \\ f_c = 13678 \times (pct\ C)^{-0.0556} \\ n = (1.617 \times 10^{-4} \times T(K) - 0.06166)^{-1} \end{cases}$$

Li C & BG Thomas, Met Trans B, 2004

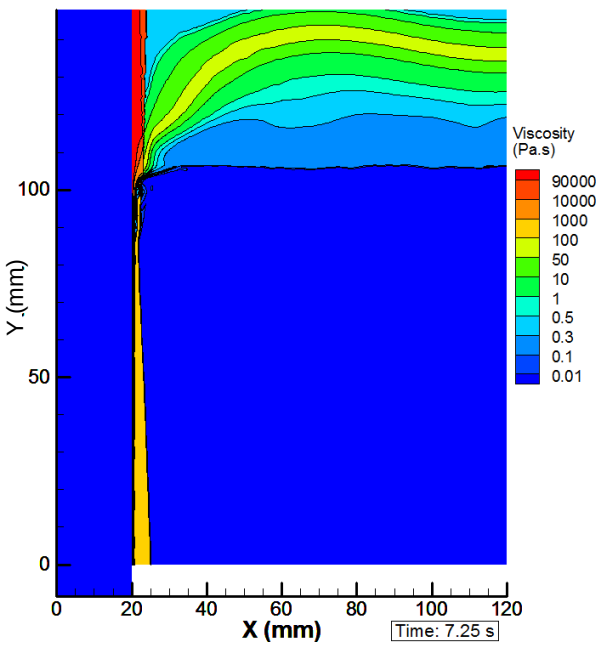
Temperature (K)	Pct Carbon (%)	Von-Mises Strain Rate (1/s)	Viscosity (Pa.s)
1800	0.001	0.01	4×10^7
1800	0.001	0.1	6.8×10^6
1800	0.001	1	1.15×10^6
1800	0.01	0.01	3.5×10^7
1800	0.1	0.01	3.1×10^7

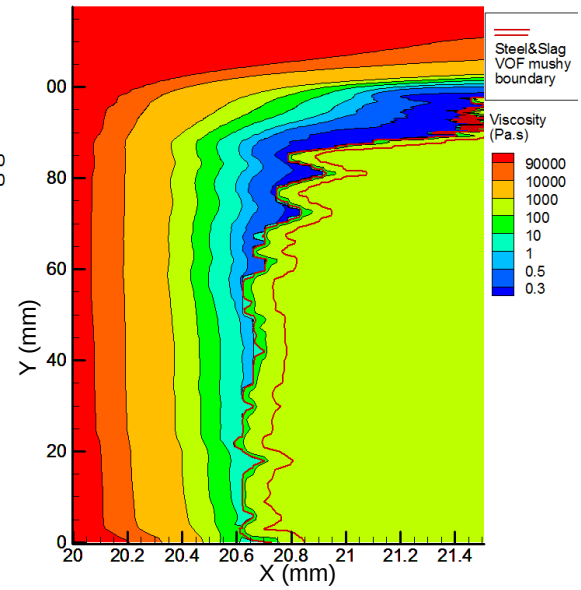
Modeling Procedure

1. Initialize phase fraction distribution (slag vs steel) with Bikerman Eqn.
2. Flow-only transient simulation to smooth phase interface (meniscus shape)
3. Thermal-only steady state simulation to establish temperature field and form initial shell
4. Coupled flow-thermal transient simulation with no mold oscillation to establish flow field
5. Fully coupled transient simulation for 8 cycles (case 1) and 2 cycles (case 2)

1 cycle of simulation takes 1 day on 6 core PC

Viscosity Solution @7.25s

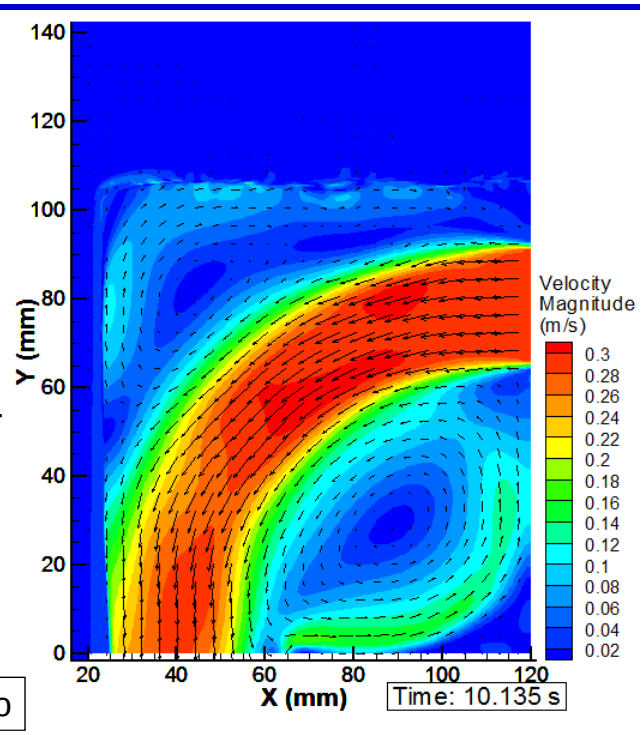




X axis elongated to show close up of gap

Velocity – case 1

- Domain at corner of NF
- Flow entering domain is form secondary recirculation zone, with velocity≈ $0.3m/s$, carrrying 3.5℃ superheat
- Generates tertiary recirculation zone in corner
- Far-field flow pattern relatively stable (for 2.5s = 8 cycles)
- far-field surface waves

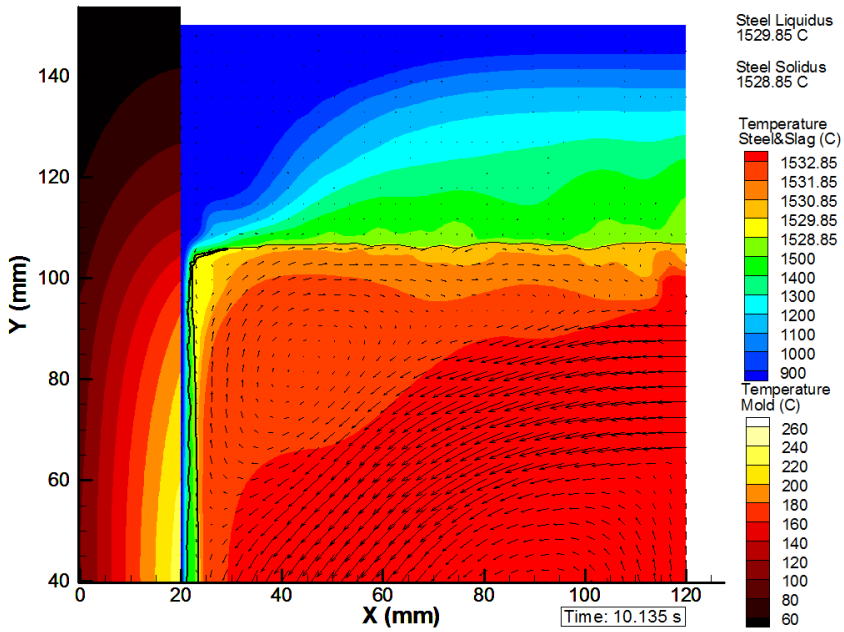


Video

Temperature – case 1

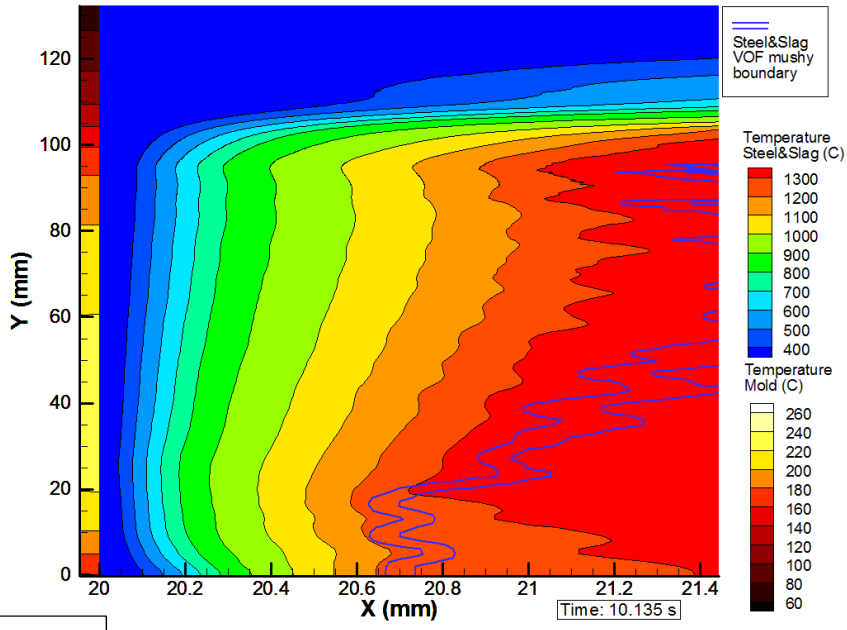
- Slag rim near meniscus represented by 1000C contour
- slow thermal response of mold

Video



Temperature in gap – case 1

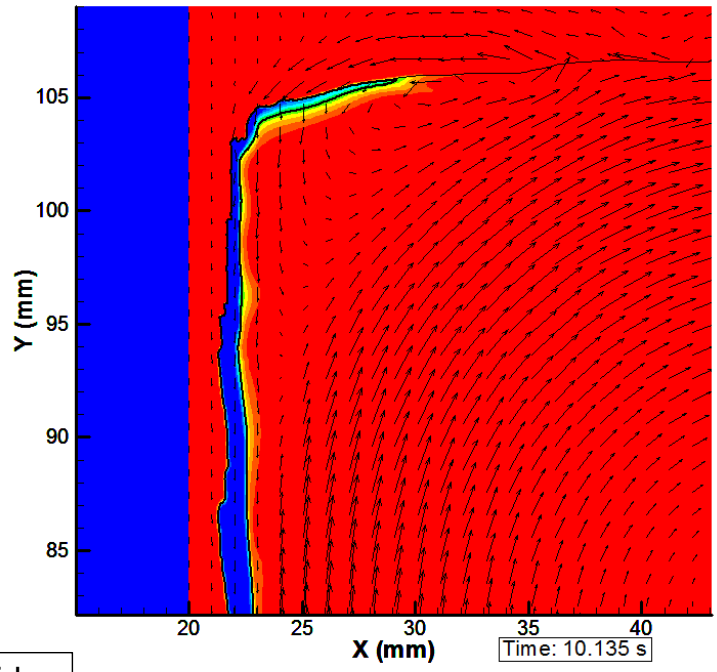
- X axis expanded
- Note: solid layer on mold wall;
- nonlinear temperature gradient across gap due to fluid flow
- Slag gap grows, (from shell tip down



Video

Initial solidification & OM formation – case 1

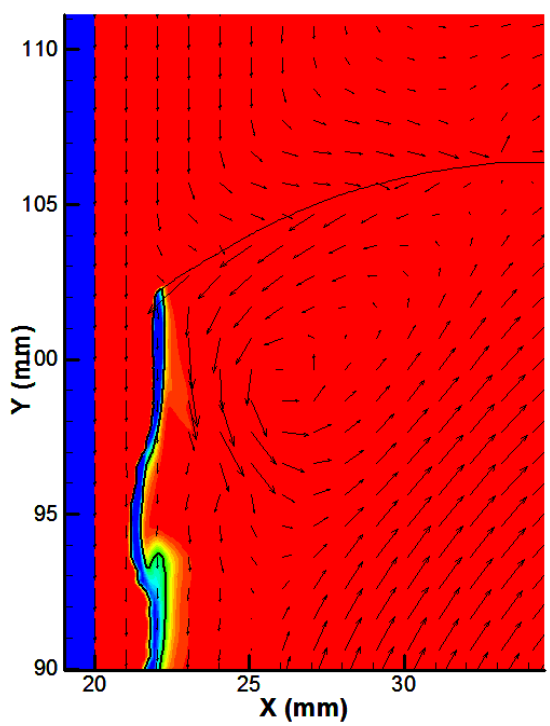
- During 8-cycle (2.5s) simulation: two occurrences of overflow happen at 7.5s and 7.9s
- As the simulation goes on meniscus cool down and freeze changes to bending behavior
- Bending is due to viscosity 10^4 times smaller and ADJUST function not in use at meniscus



Video

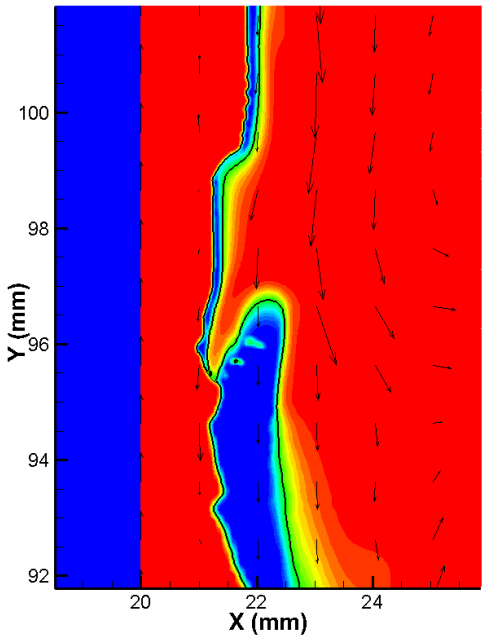
Initial solidification & OM formation – case 2

- Duration 2 cycles
- Shell is rigid after solidification (turning blue)
- Overflow happens when mold has maximum speed upward
- Small hook forms (even with no undercooling)
- Smaller slag gap compared to bending mechanism

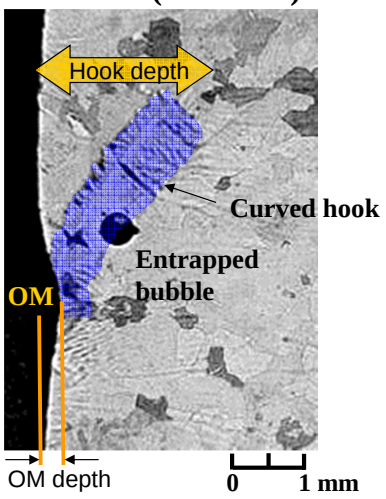


Video

Oscillation Marks and Hooks



Side view (of section)

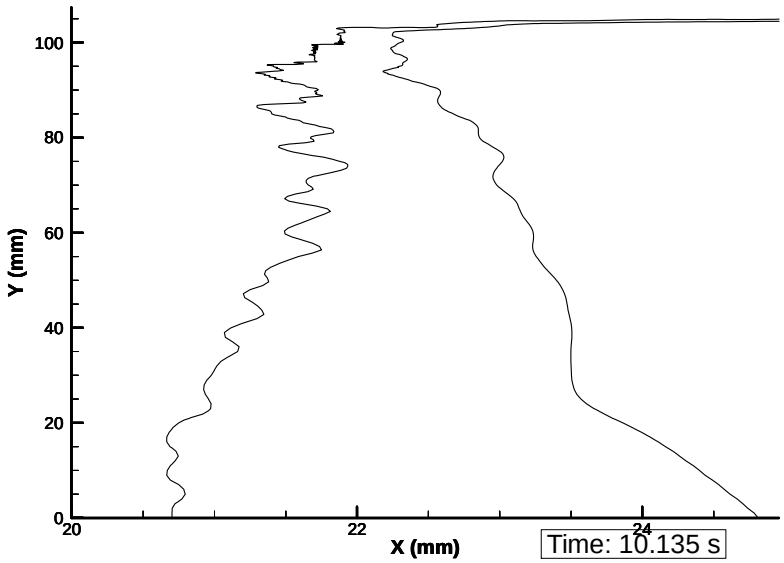


J. Sengupta, H. Shin, BG Thomas, et al, Acta Mat., 2005

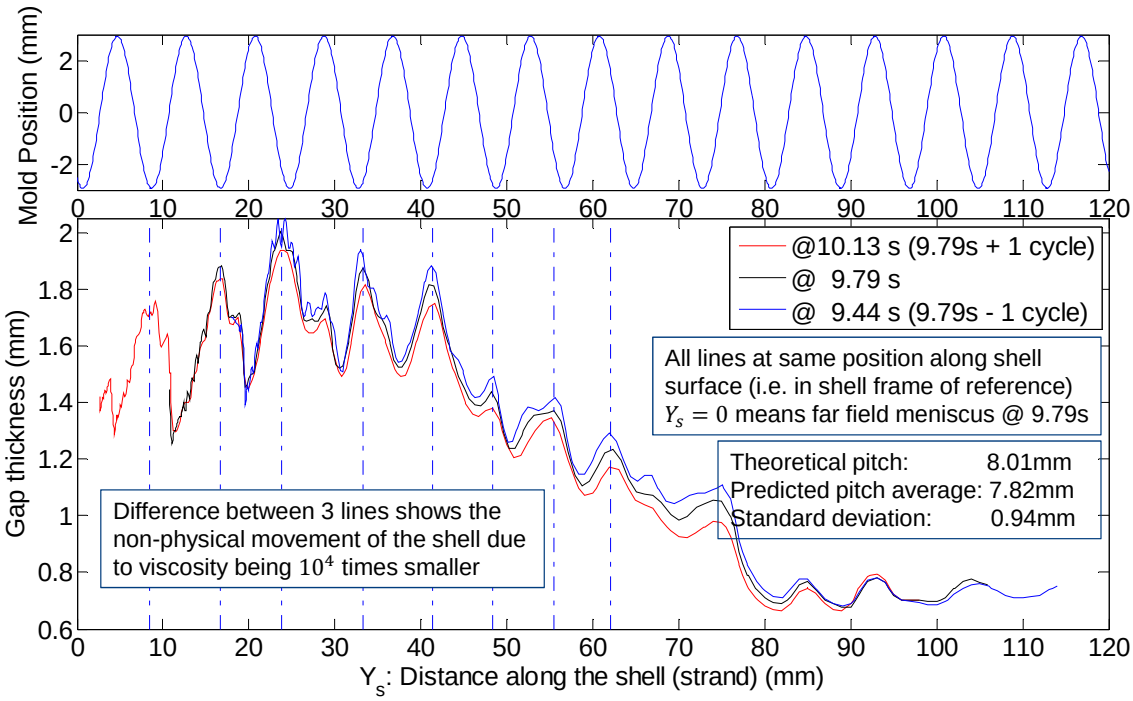
Shell & slag gap profile – case 1

- X axis expanded
- The ADJUST function is capable of keeping OM shape, but still allows too much movement
- Slag gap gets wider as simulation goes on

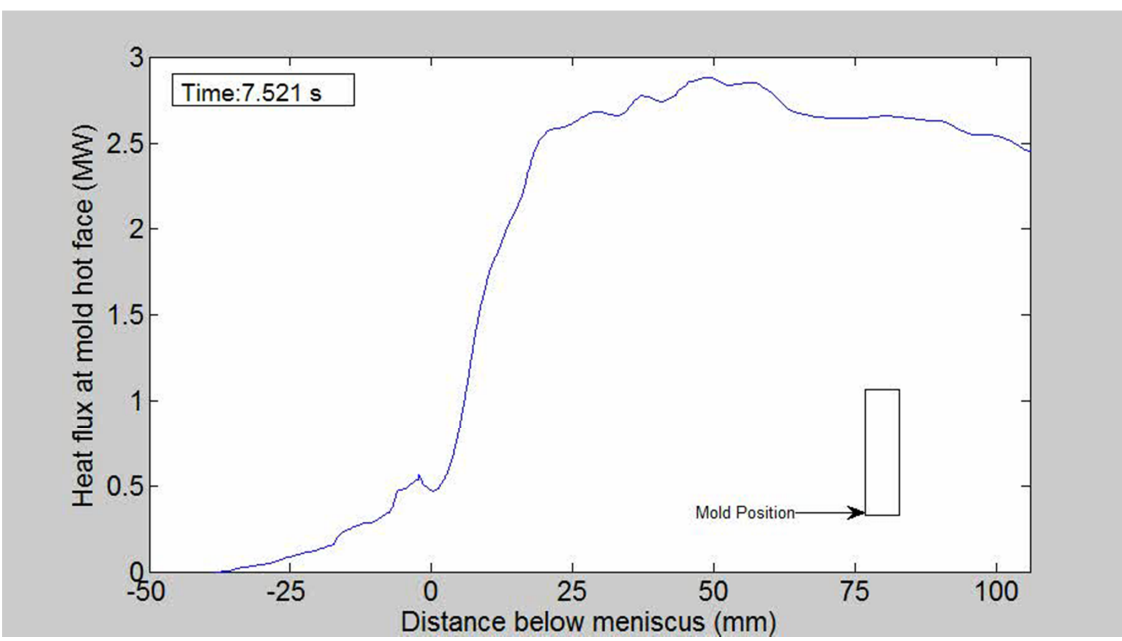
Video



Predicted strand surface profile along the strand

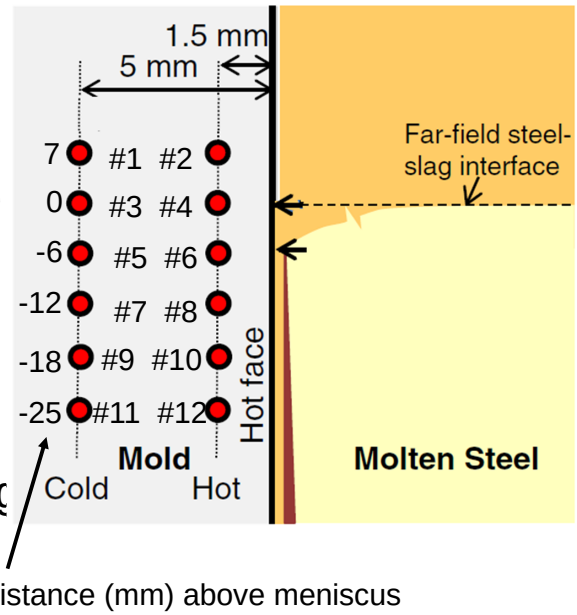


Heat flux at mold hot face

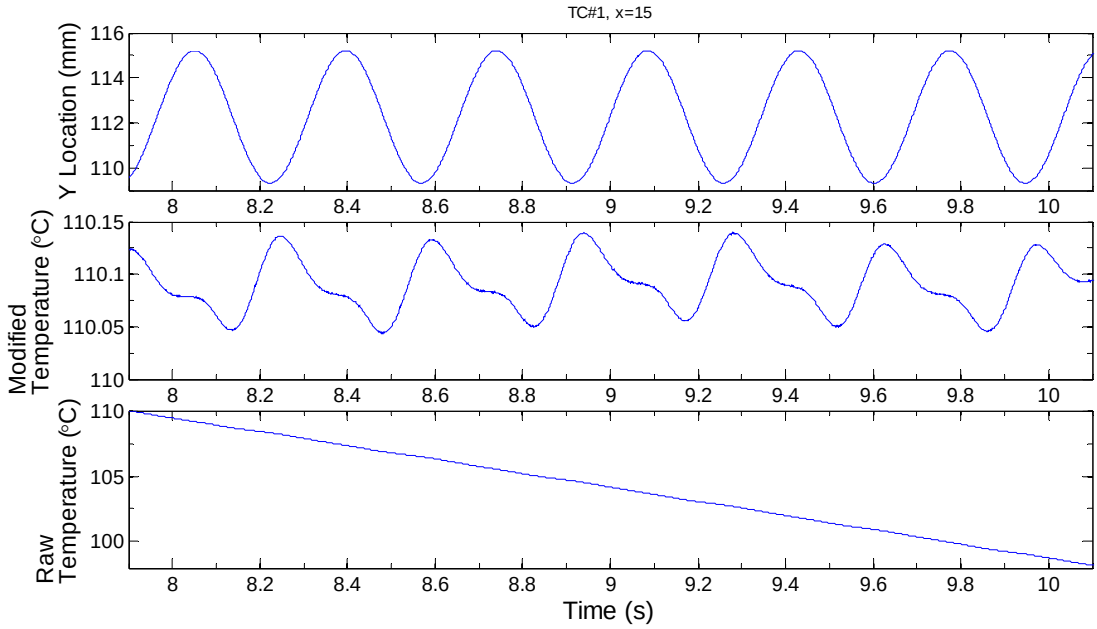


Thermocouple locations

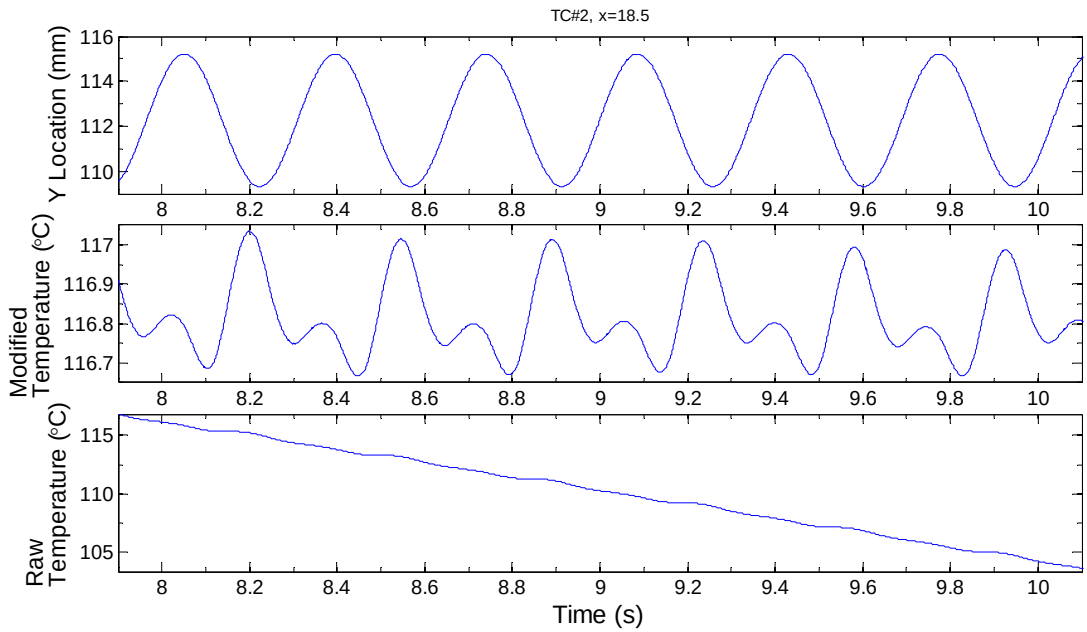
- Due to insufficient heat in meniscus region, mold temperature is constantly dropping during simulation
- In order to extract the temperature fluctuation due to oscillation, the TC temperature history is fitted to a cubic function, which captures the cooling trend.
- A modified temperature is then acquired by subtracting the cubic function



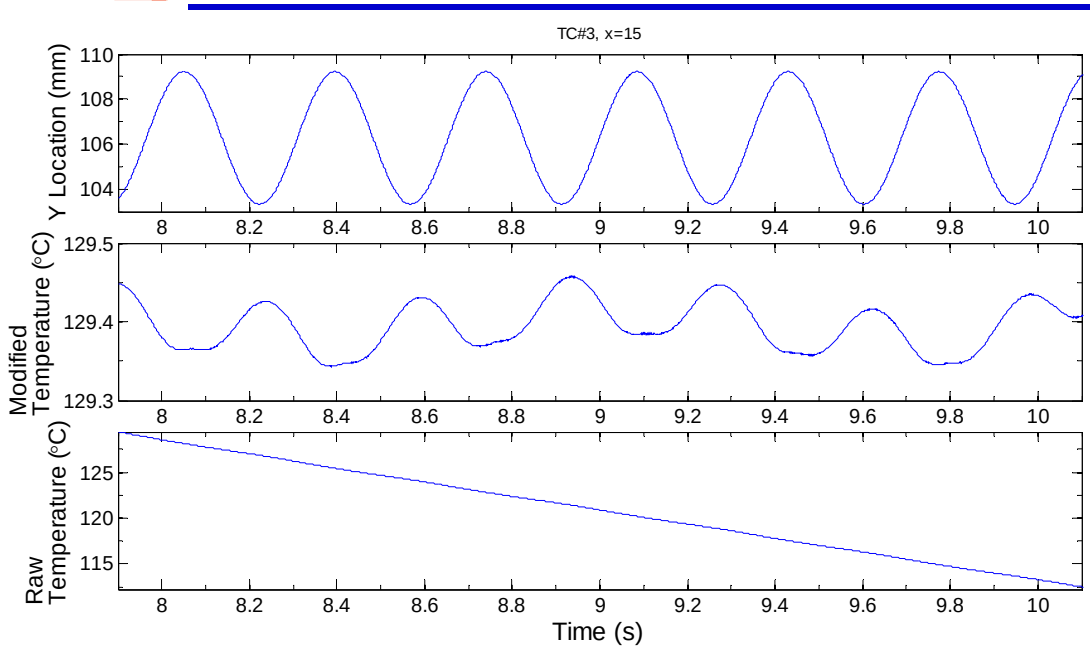
Thermocouple #1 temperature fluctuations



Thermocouple #2 temperature fluctuation

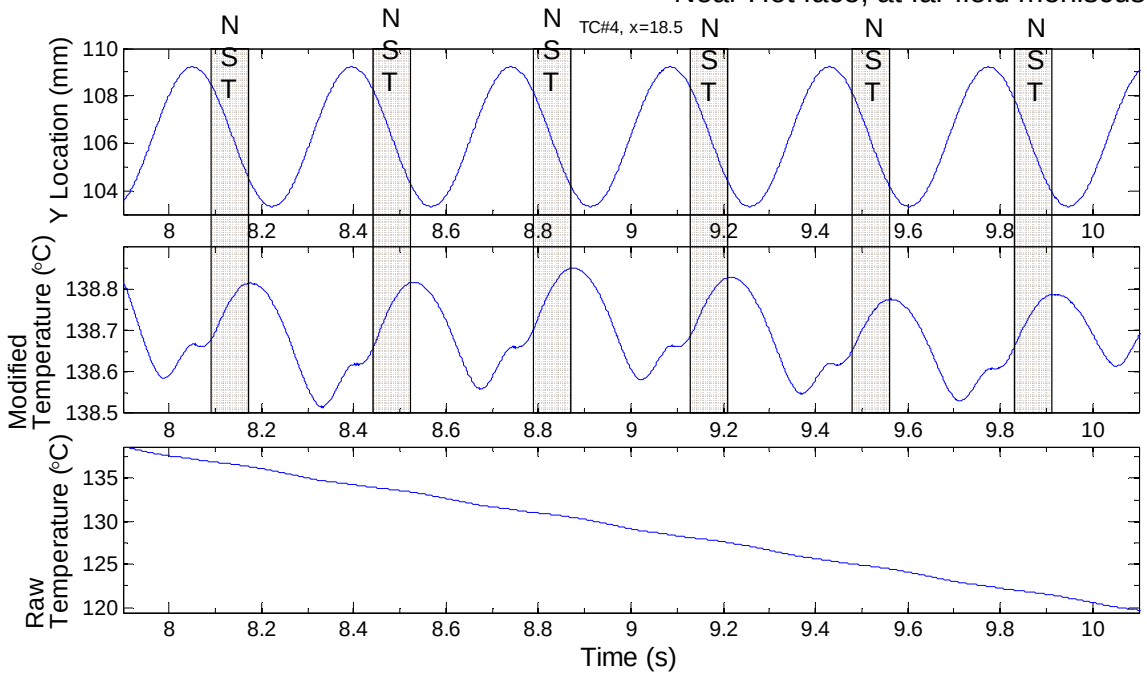


Thermocouple #3 temperature fluctuation

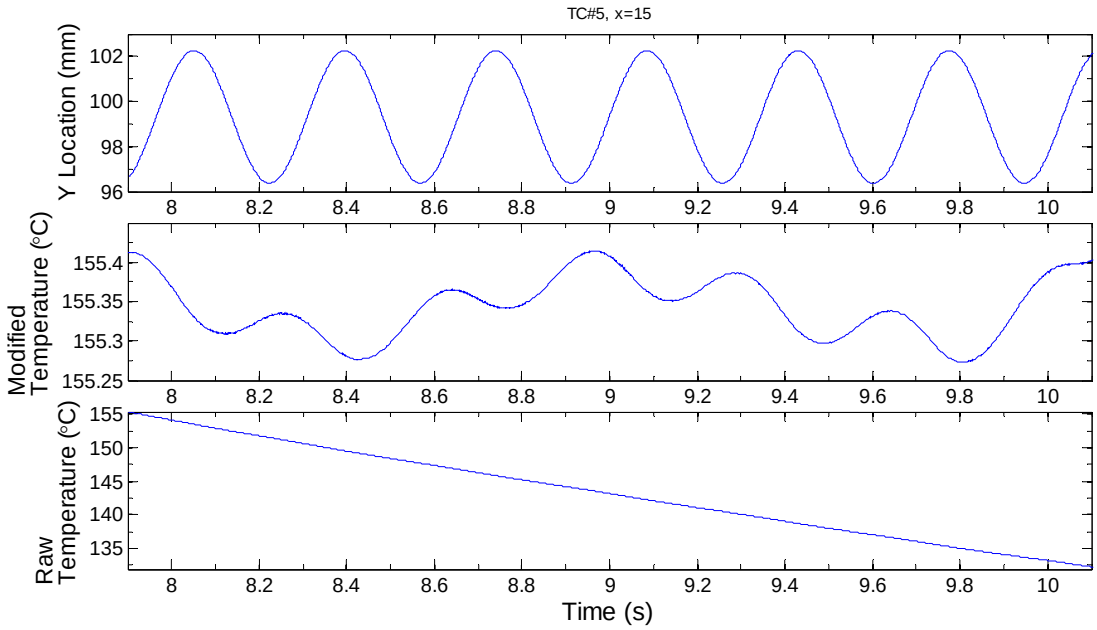


Thermocouple #4
~0.3C temperature fluctuations

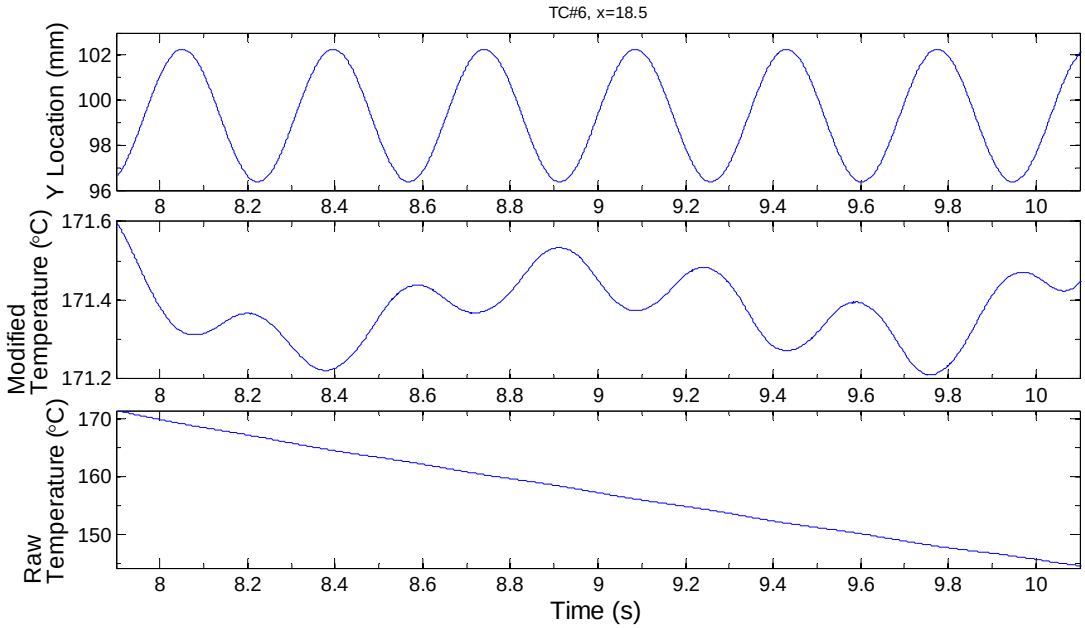
Near Hot face; at far field meniscus



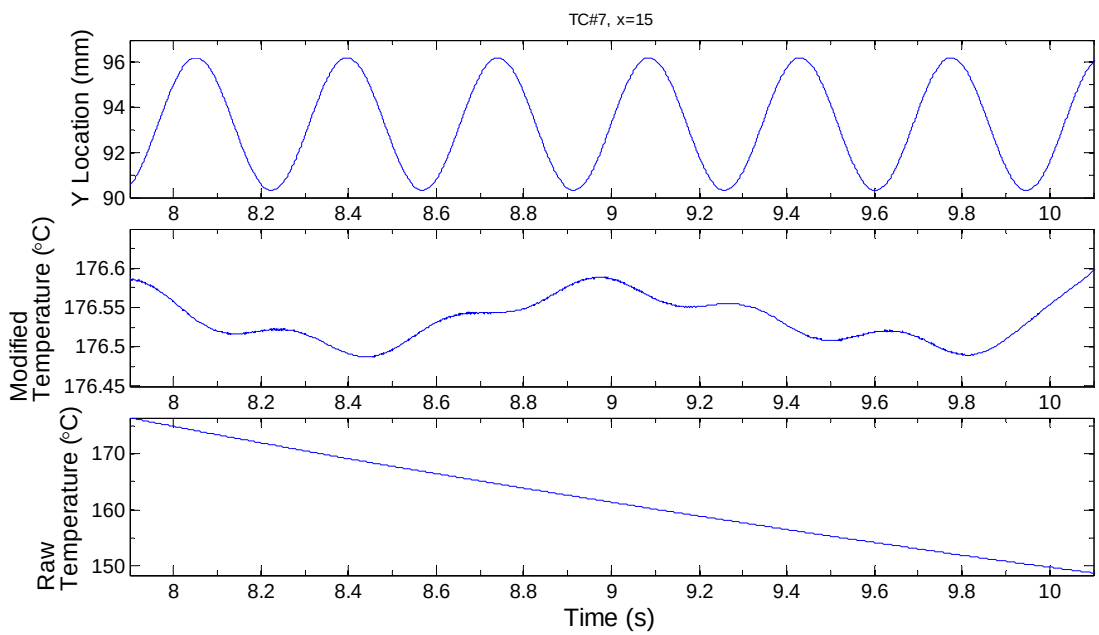
Thermocouple #5
temperature fluctuation



Thermocouple #6 temperature fluctuation

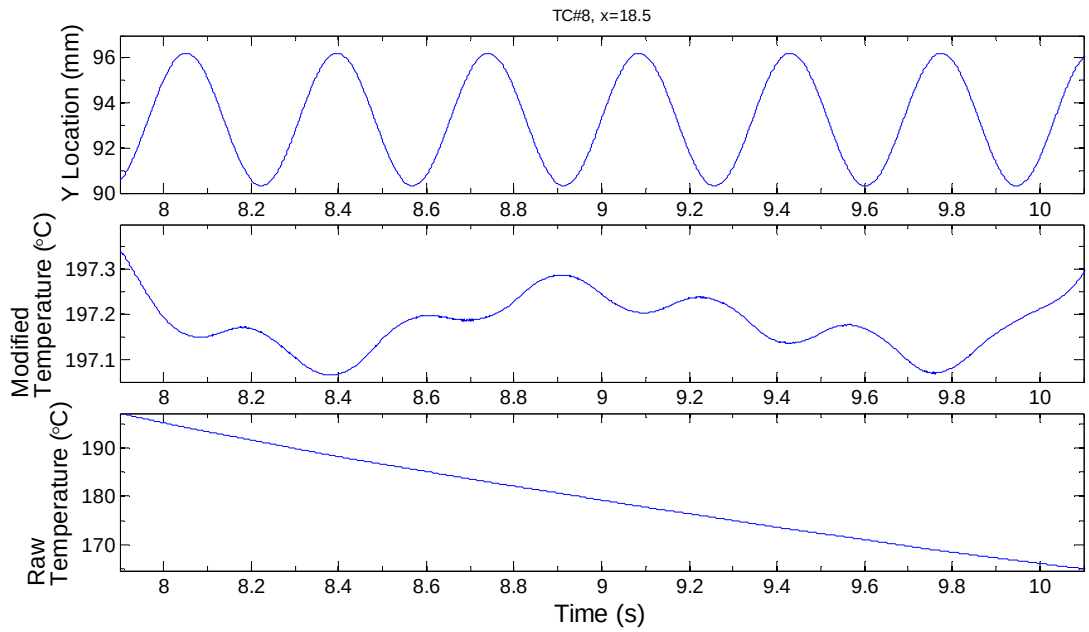


Thermocouple #7 temperature fluctuation

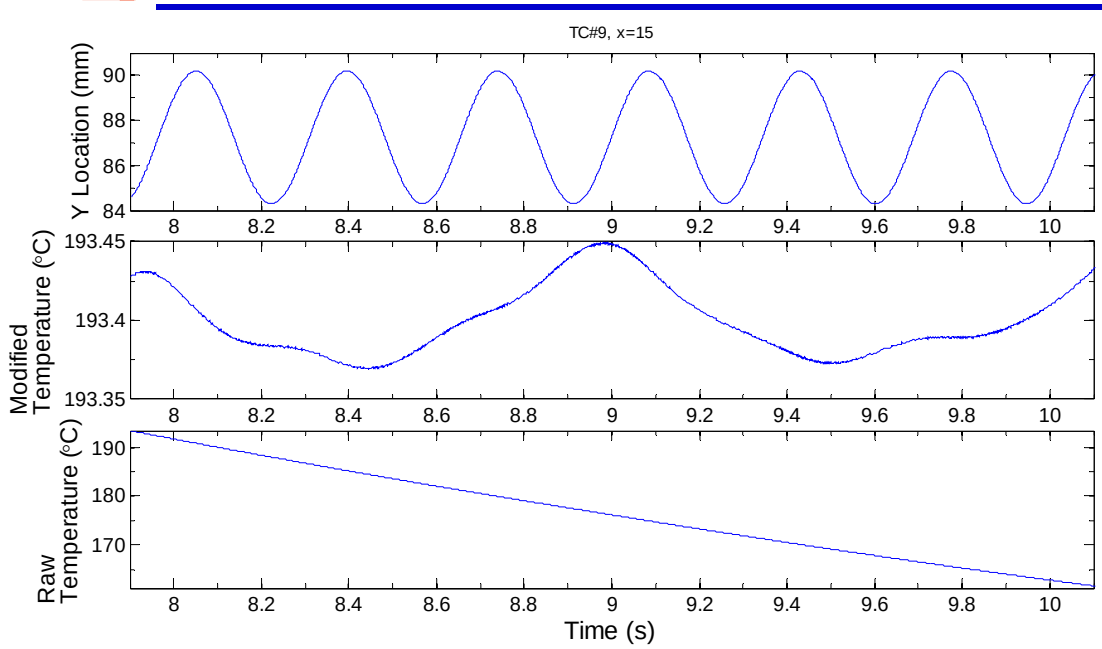


Thermocouple #8 temperature fluctuation

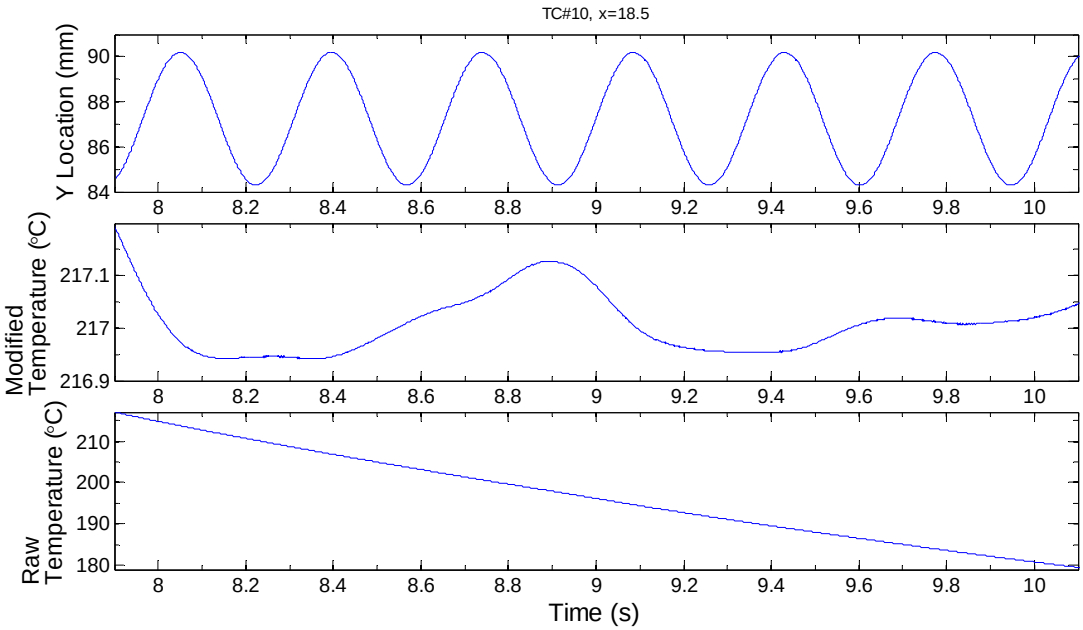
Near Hot face; 12 mm below field meniscus



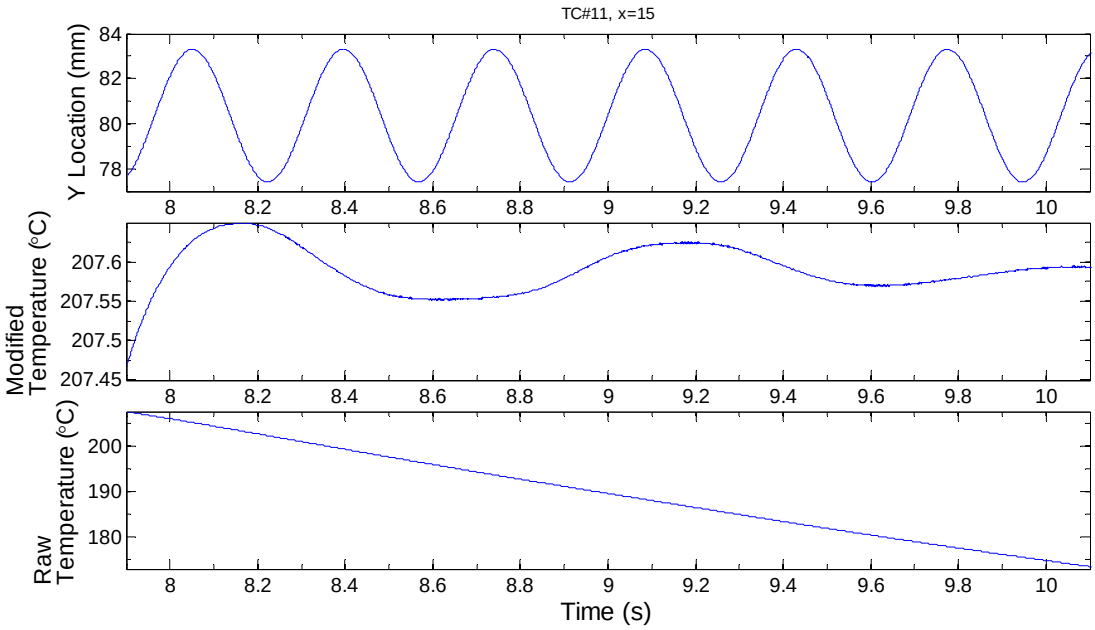
Thermocouple #9 temperature fluctuation



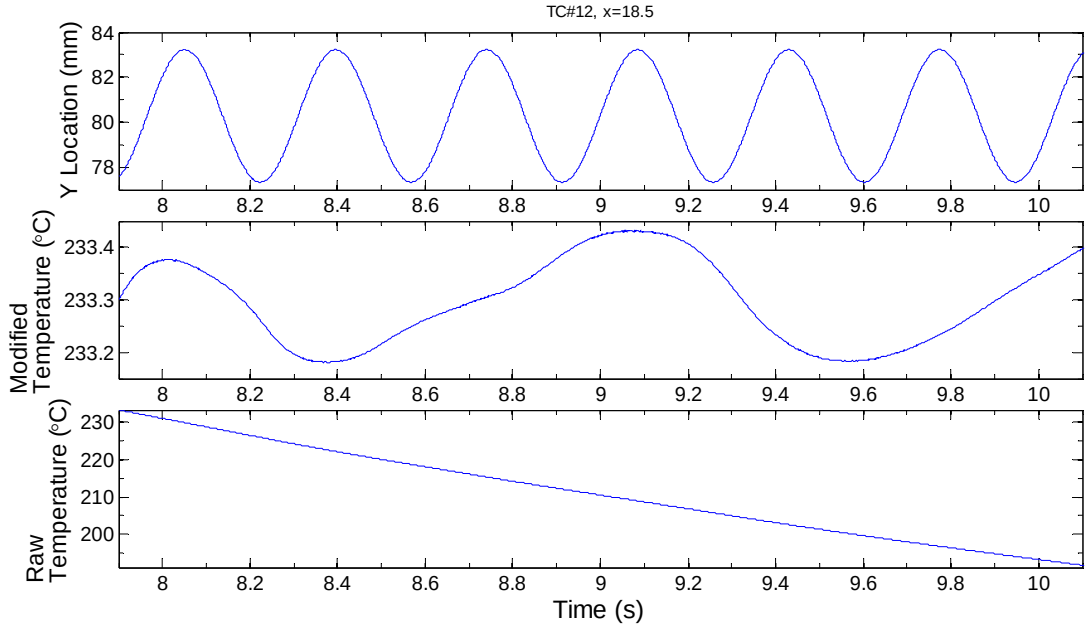
Thermocouple #10 temperature fluctuation



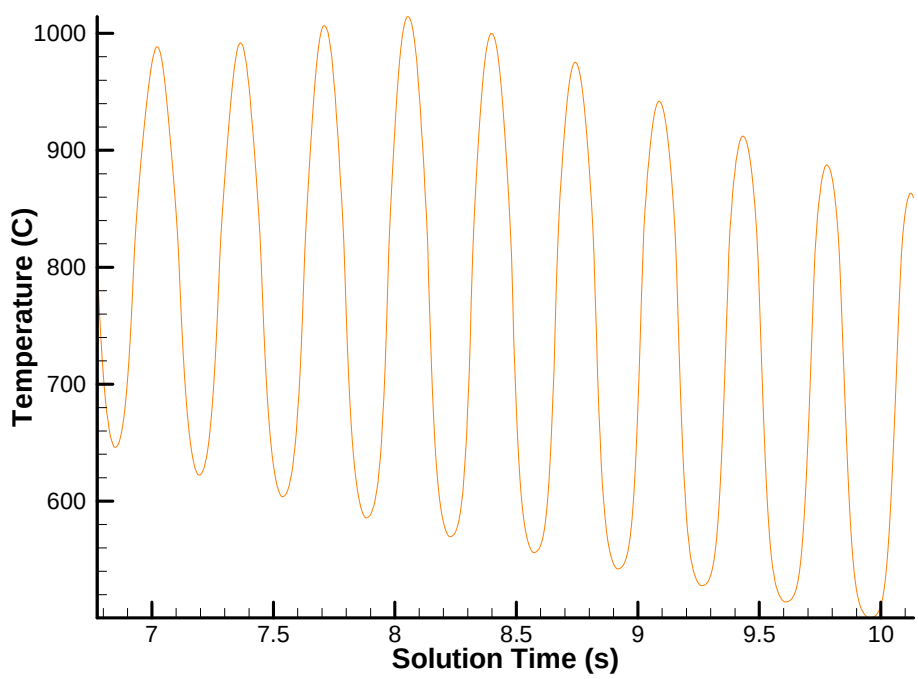
Thermocouple #11 temperature fluctuation



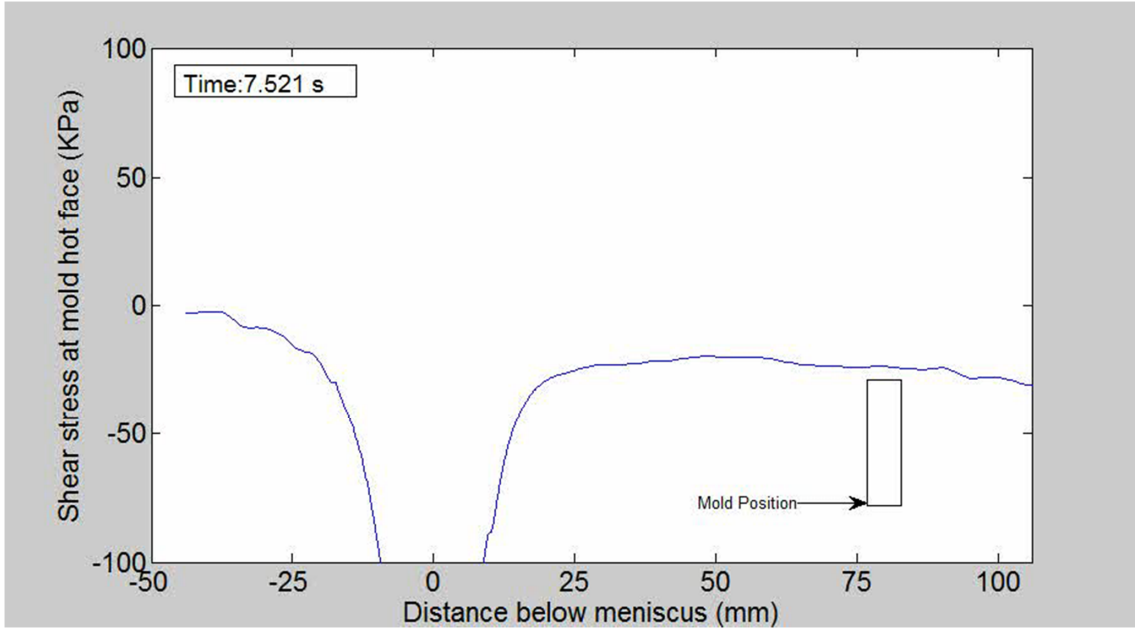
Thermocouple #12 temperature fluctuation



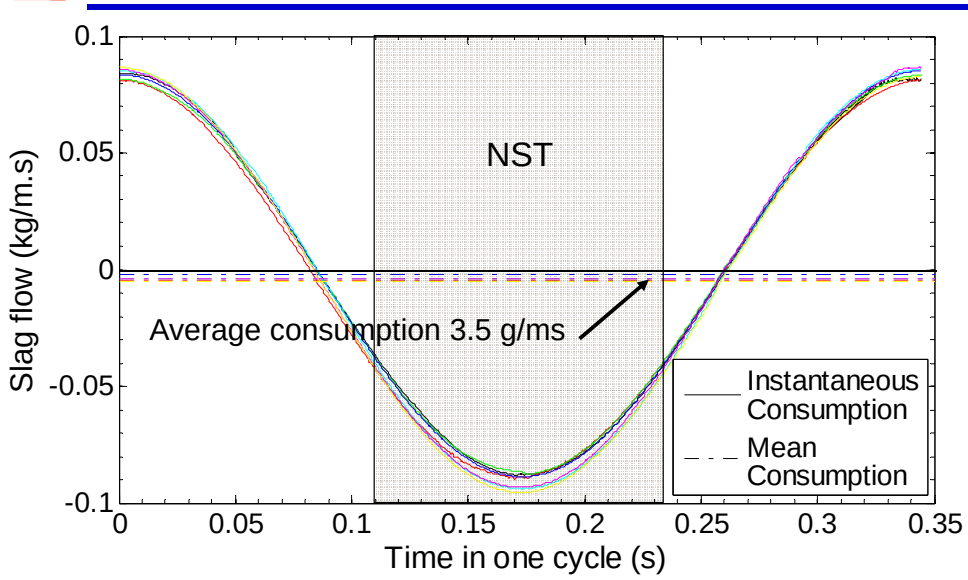
Slag temperature near meniscus at x=21mm, y=106mm



Shear stress at mold hot face



Slag consumption for 7 cycles



Cycle #	1	2	3	4	5	6	7	Average
Mean Consumption ($^{g}/_{m \cdot s}$)	2.3	4.6	2.2	2.3	3.8	3.8	5.3	3.5

Conclusion - modelling

- New thermal-fluid VOF model of mold, slag, powder, solidifying steel shell, and gap has been developed to investigate initial solidification
- Model can predict oscillation mark formation, with different mechanisms (both bending and overflow) according to different material property (steel viscosity)

Conclusion – OM mechanism

- Low viscosity steel (nonphysical) - **Bending mechanism**
  - OM forms when mold at lowest position
  - Wider meniscus gap, causing lower meniscus heat flux and less mold TC temperature variations
  - Very wide contoured OM shape
  - Slag consumption profile similar to previous work, but average consumption is low
  - Nonphysical because frozen meniscus would break under so much bending
- Rigid steel viscosity - **Overflow mechanism**
  - Rigid shell (moving downward) combined with meniscus movement exceeds
  - Occurs when mold has maximum speed going up
  - OM shape is shallower than that from bending mechanism
  - Seems physically reasonable
  - We expect higher meniscus heat flux, larger TC temperature fluctuation.

Future work

- Eliminate the cooling trend by improving powder surface inlet boundary condition
- Improve realism of shell behavior at meniscus by increasing viscosity (if possible) or fine tune the ADJUST function zone
- Validate with more measurements
- Parametric studies

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)