CCC Annual Report

UIUC, August 14, 2013

Meniscus Region Thermo-Fluid Model For Predicting Transient Heat Transfer and Slag Consumption

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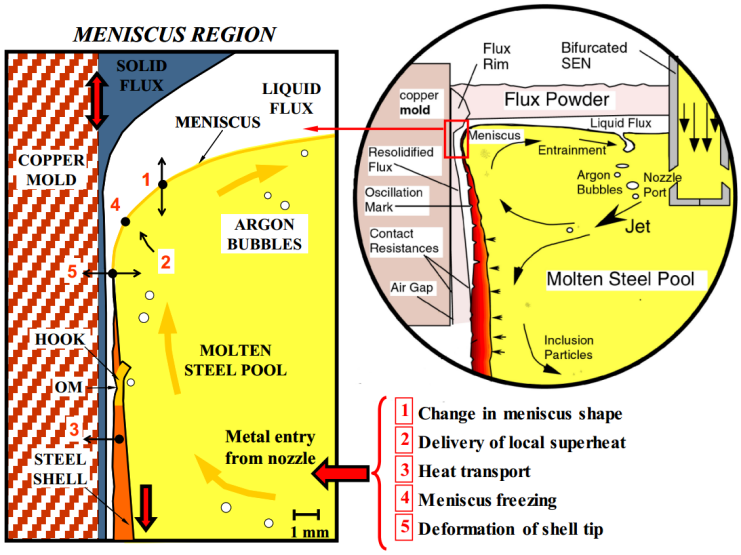
Outline

- Objectives
- Model Description
- Previous work
- Heat Transfer Validation
  - Experiment Procedure and measurements obtained – Badri and Cramb
  - Domain, Boundary conditions , mesh and material properties for model
  - Steady state Heat flux and temperature contours
  - Animation of 1 cycle of oscillation in meniscus region
  - Comparison with measured temperature
- Slag Consumption Validation
  - Domain and BCs for model
  - Animation of 1 cycle of oscillation
  - Model prediction Vs. measured values at plant
- Parametric Studies
  - Casting Speed
  - Stroke
  - Frequency
  - Modification Ratio
- Conclusions
- Future Work

Objectives

- **Develop** a transient thermo-fluid model of meniscus behavior
  - Incorporate governing physical phenomena
- **Validate** model with
  - thermocouple measurements
  - slag consumption measurements
- **Predict**
  - Transient heat flux near meniscus region.
  - Transient temperature profile in mold, slag and steel region.
  - Thickness of liquid slag layer above meniscus.
  - Transient flow behavior of the slag in the meniscus region.
  - Effect of casting and mold oscillation parameters on slag consumption:
    - Casting speed
    - Frequency
    - Stroke
    - Modification Ratio

Meniscus Phenomena



Sengupta, J., and B. G. Thomas, "Visualization of Hook and Oscillation Mark Formation Mechanism in Ultra-Low Carbon Steel Slabs During Continuous Casting," JOMe, (Journal of Metals – electronic edition), December 2006.

Model Description

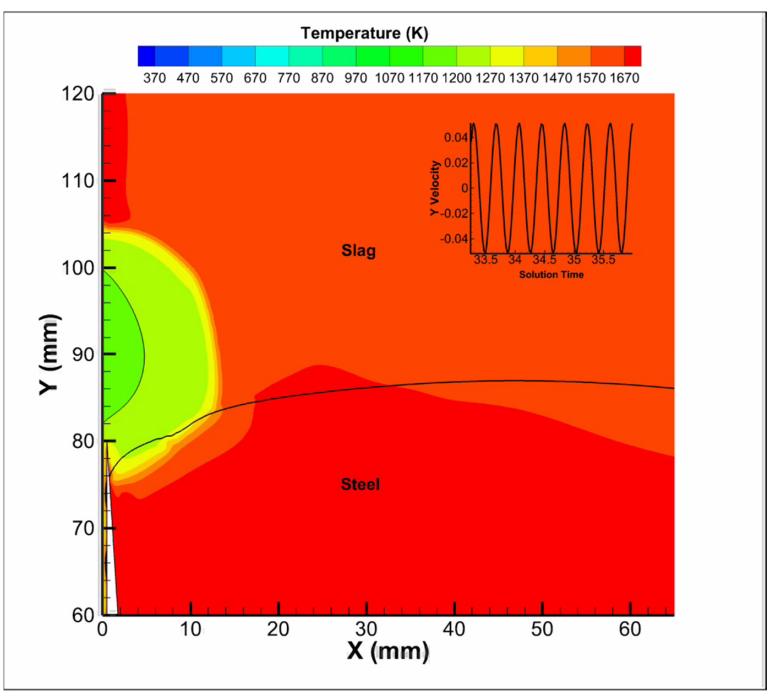
- 2D simulation of the centerline of the Wide/Narrow face of the mold as the simplification of the 3D mold.
- Total slag thickness and Solid shell thickness are fixed and are not part of the solution domain but calculated based on actual casting conditions using CON1D.
- Only a small region beside the mold hot face is modeled.
- solidification of slag is modeled by temperature dependent properties.
- Steel properties and temperature kept constant to model liquid steel and constant supply of heat.

Equations to solve–

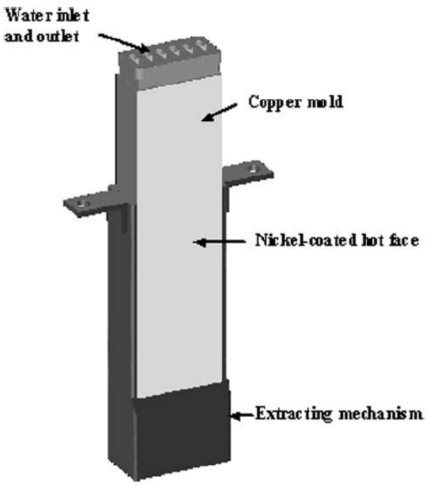
1. **Fluid Flow**
   k-ω SST Model
2. **Heat Transfer**
   Transient 2-D Energy Equation
3. **Interface between Slag and molten Steel**
   VOF Model – Explicit Scheme (2 non-interpenetrating phases)
   - Surface Tension
   - Wall Adhesion Model

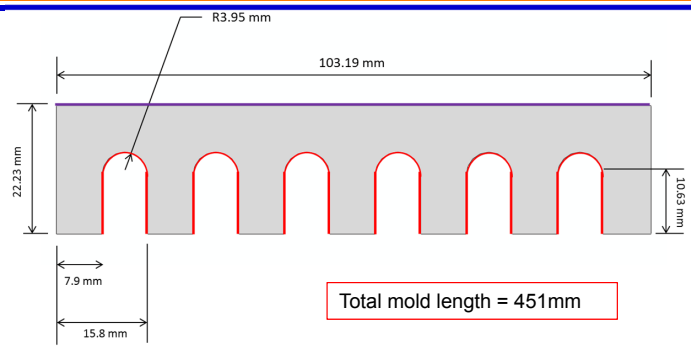
Pressure-Velocity Coupling – PISO for Transient VOF
Geo-Reconstract for surface tracking
Pressure Interpolation Scheme - PRESTO!

Previous Work: CCC 2012

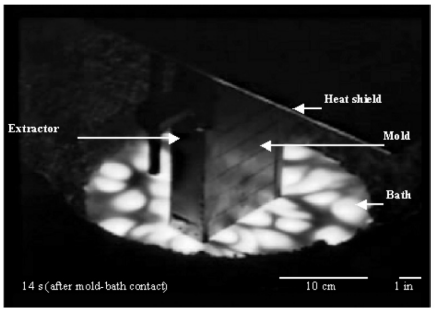


Current Work
Heat Transfer Validation Case: Badri Experiment



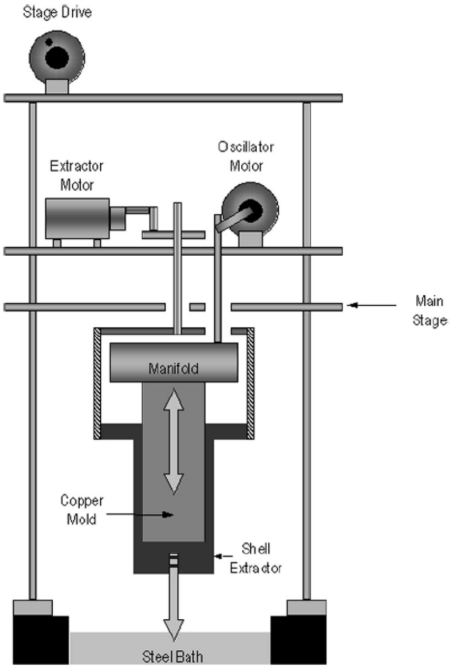


Total mold length = 451mm



A. Badri, T. T. Natarajan, C. C. Snyder, K. D. Powers, F. J. Mannion, and A. W. Cramb: A Mold Simulator for the Continuous Casting of Steel, Part 1, Steel Shell Solidification Profiles, Met Trans B, 2005

Badri Experiment: Procedure and Casting Conditions



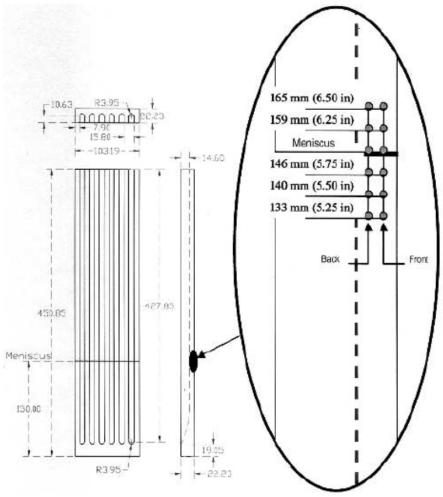
Step	Description	Time
1	Mold simulator placed atop the furnace crucible containing the liquid steel and mold flux	
2	Oscillator drive activated to start the oscillation of the mold	
3	Mold and extractor lowered into the bath	>=2sec
4	3 inch of the hot face is exposed to the liquid steel	
5	Allow sometime to grow the shell to prevent tearing during extraction	3 sec (ref: Badri Paper, 2005)
6	Extractor lowered at constant velocity for additional 3 inches	6 sec
7	Entire assembly is removed from the furnace	>= 3 sec

Casting Condition:

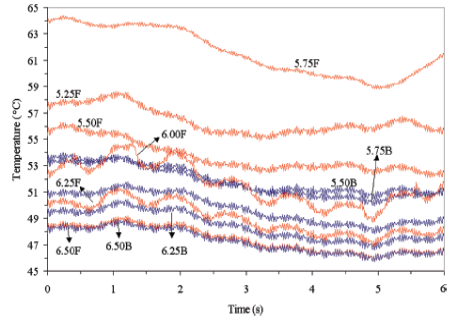
Stroke = 6.3 mm
Oscillation Frequency = 1.3 Hz
Casting speed = 12.7 mm/s
Liquid Pool Depth = 6.5 mm

A. Badri, T. T. Natarajan, C. C. Snyder, K. D. Powers, F. J. Mannion, and A. W. Cramb: Met Trans B, 2005

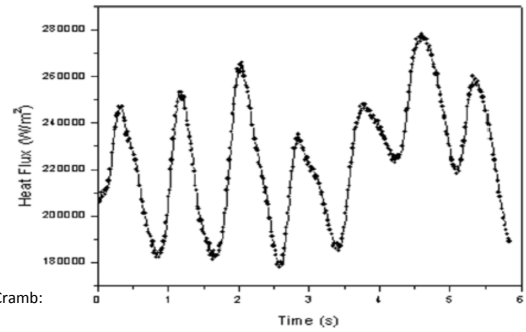
Badri Experiment: Thermocouple measurements and Inverse Heat flux results



For Ultra Low Carbon Steels



1D Inverse ⇩ Heat flux model



A. Badri, T. T. Natarajan, C. C. Snyder, K. D. Powers, F. J. Mannion, and A. W. Cramb: Met Trans B, 2005

CON1D Steady-State Simulation:

Badri Experiment

Fast method to find: slag layer thickness to produce reasonable heat flux profiles

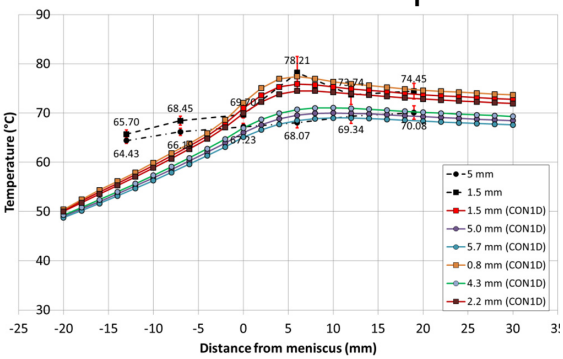


Fig: Temperature Predictions at TC locations

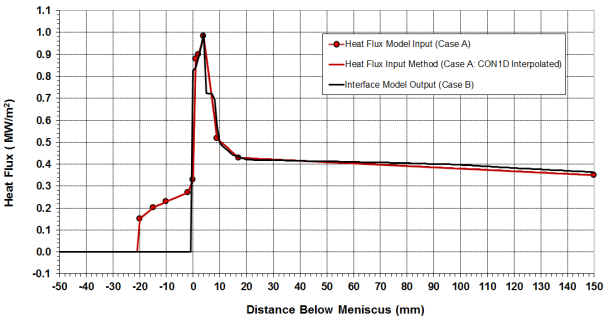
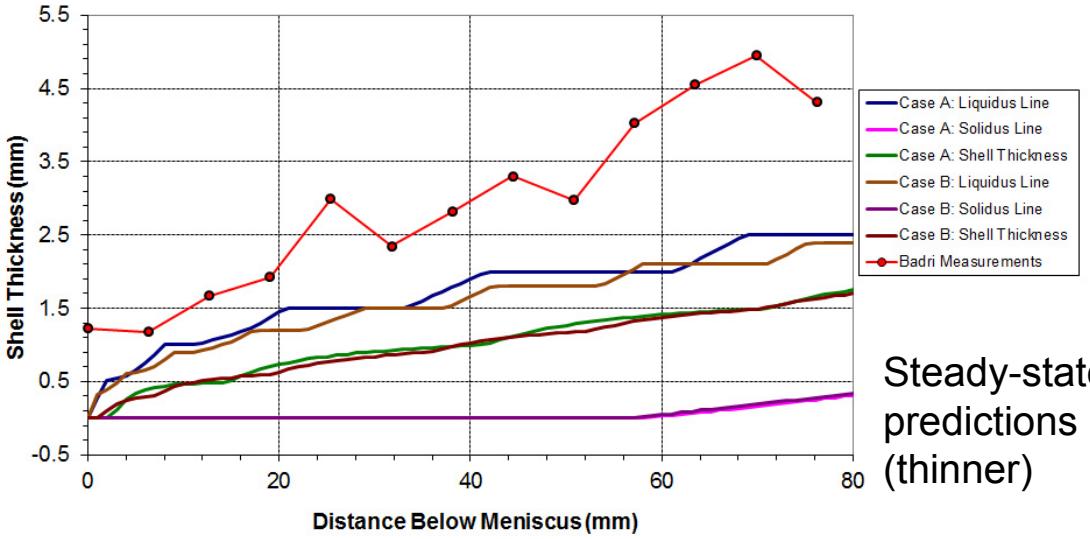


Fig: Comparison between Heat Flux between Case A and Case B

Case A: Input Heat Flux Profile
Case B: Calculate Heat Flux with Interface Model

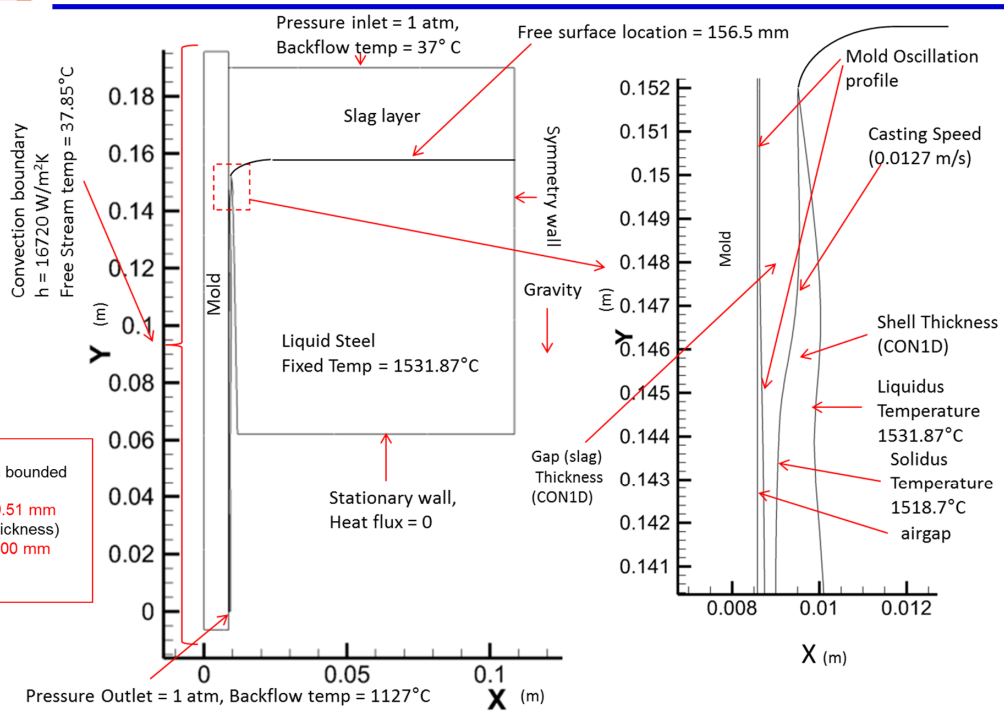
Shell Thickness: CON1D Prediction vs. Badri Measurements

"transient" measurements (thicker)



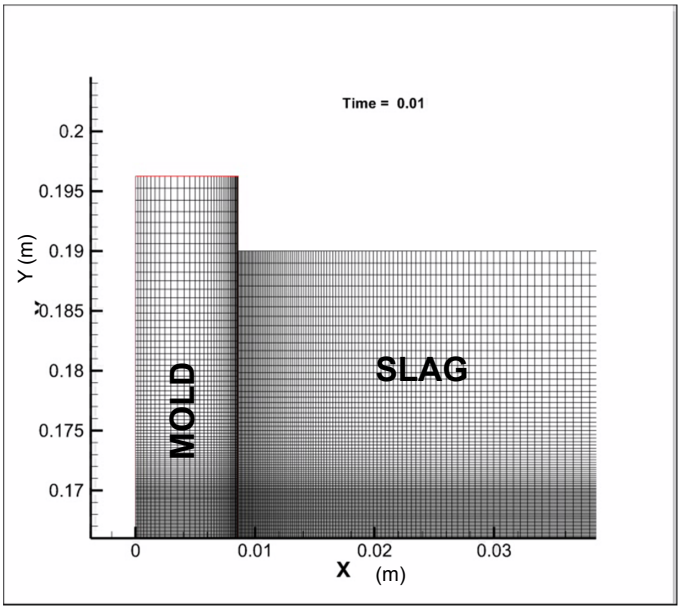
Steady-state predictions (thinner)

Domain and Boundary Conditions

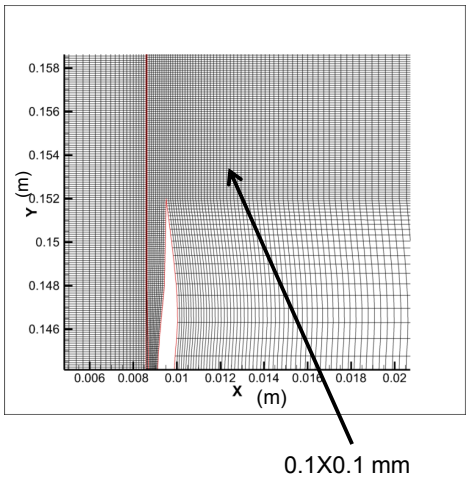


Solidifying zone:
Rectangular Region bounded by -
X = 8.58 mm , X = 9.51 mm
(8.58 mm is mold thickness)
Y = 0mm , Y = 190.00 mm
Melting Zone:
Rest of the Domain

Mesh and "Sliding"



Solid domain 2-phase liquid domain



Cells: 99064
Faces: 205149
Nodes: 102240
Max. aspect ratio = 61 (right corner of the domain)
9 cells in the gap

Casting Conditions & Material Properties

Steel Properties:

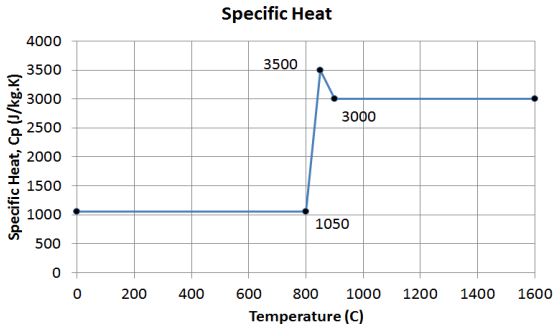
- Constant properties for Steel was used
  - Density = 7000 Kg/m^3
  - Specific Heat, Cp = 700 J/Kg-K
  - Thermal Conductivity = 30 W/m-K
  - Viscosity = 0.0063 Kg/m-s
  - Melting Temperature = 1531.87° C
  - Solidification Temperature = 1518.7°C

Casting Conditions:

Stroke = 6.3 mm
Sinusoidal
Oscillation Frequency = 1.3 Hz
Casting speed = 12.7 mm/s
= 0.762 m/min

Slag Properties:

Density = 2500 Kg/m^3
Specific Heat, Cp



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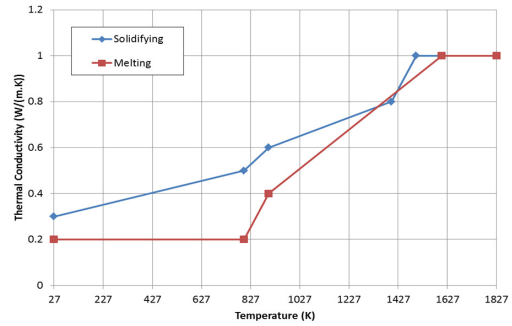
Slag Properties – Spatial and Temperature Variation

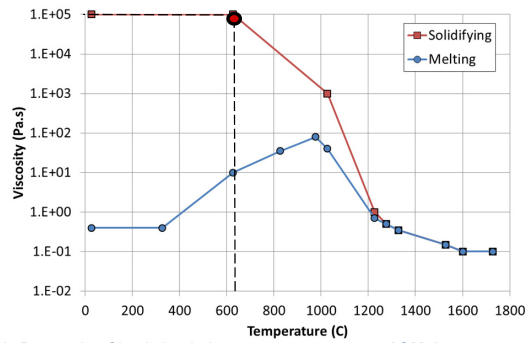
- **Thermal Conductivity***

Solidifying zone:
Rectangular Region bounded by -
X = 8.58 mm , X = 9.51 mm
(8.58 mm is mold thickness)
Y = 0mm , Y = 190.00 mm
Melting Zone:
Rest of the Domain



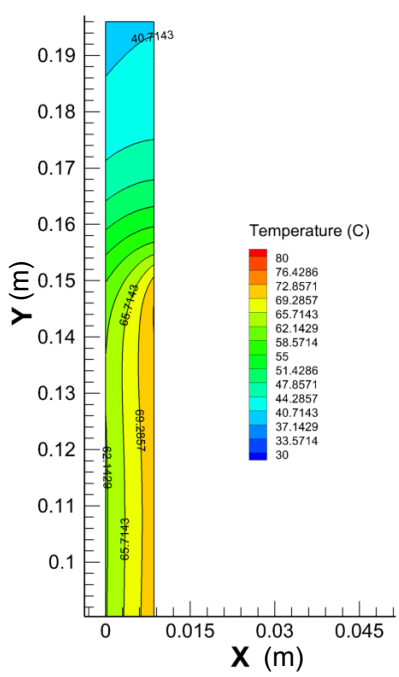
- **Viscosity***

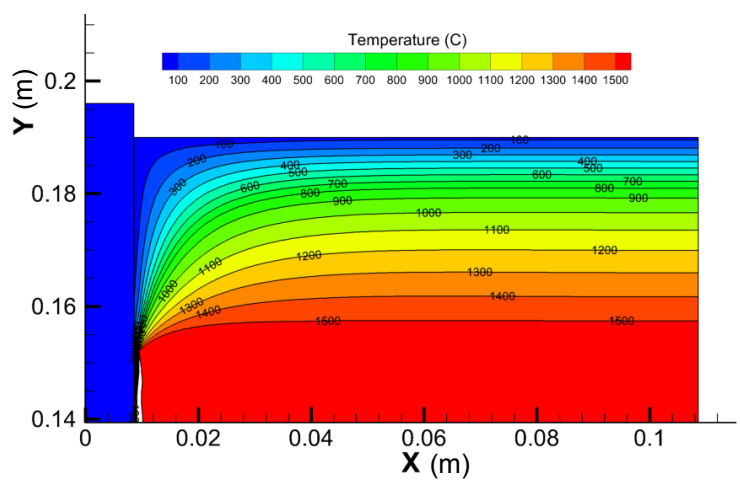
Surface tension between liquid steel and liquid slag = 1.3 N/m
Contact angle = 160°*



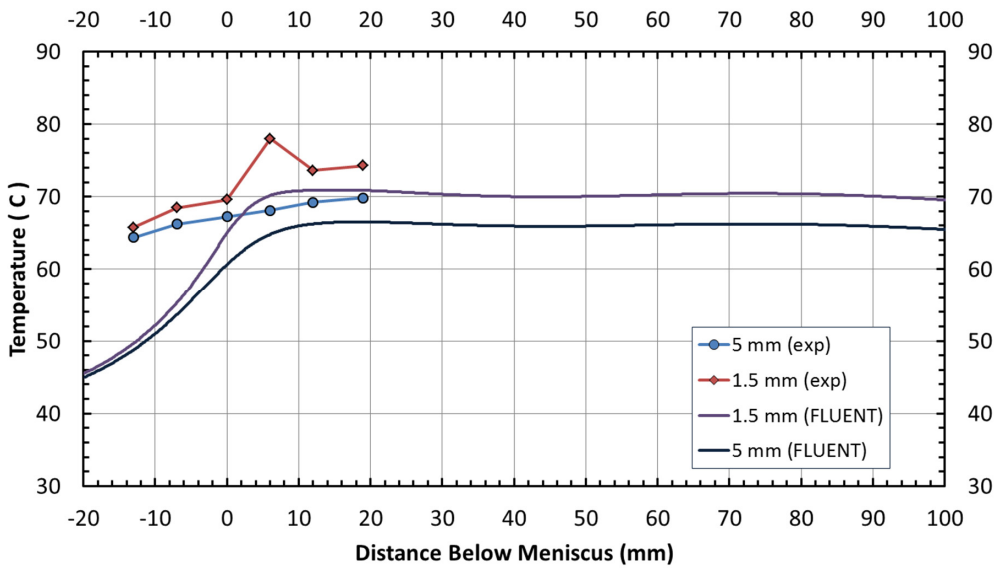
*Ojeda, C., B.G. Thomas, J. Barco, and J.L. Arena, "Model of Thermal-Fluid Flow in the Meniscus Region During An Oscillation Cycle", AISTech 2007, Steelmaking Conference Proc., (May 7-10, Indianapolis, IN), AIST, Warrendale, PA, Vol. 1, 2007

Temperature Contour: Slag & Mold Region



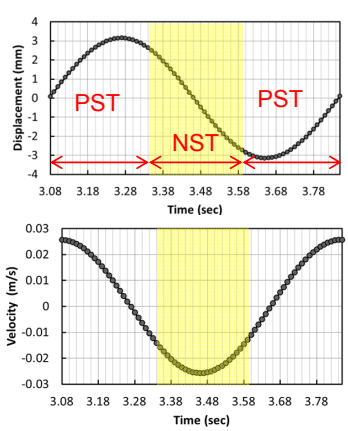


Temperature prediction Vs. Badri Measurements (Time-average)



Transient Case: Temperature Contour

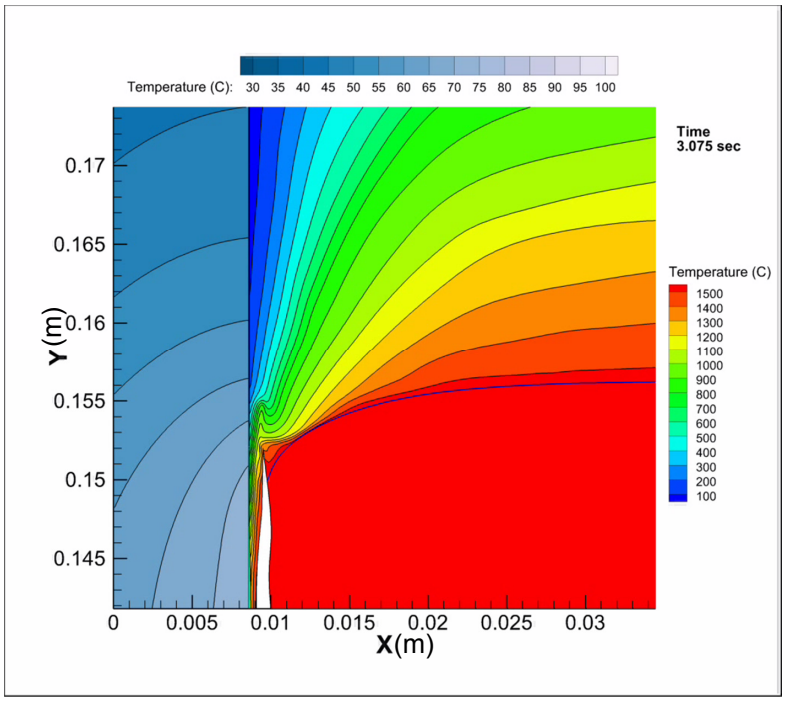
Osc. Start time = 3.085 sec
Osc End time = 3.85 sec



NST: Negative Strip Time
PST: Positive Strip Time

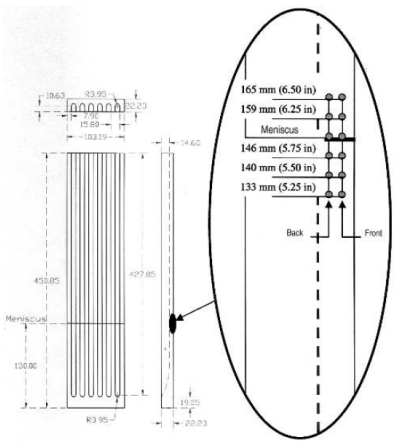
Casting speed : 12.7 mm/s

Animation of 5th oscillation



Thermocouple (TC) locations – Badri's experiment

No of TC = 12
Distance from hot face = 1.5 mm, 5.00 mm



TC positions with respect to meniscus

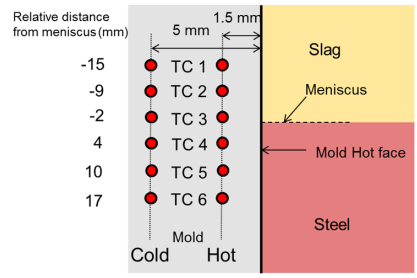


Fig: TC locations

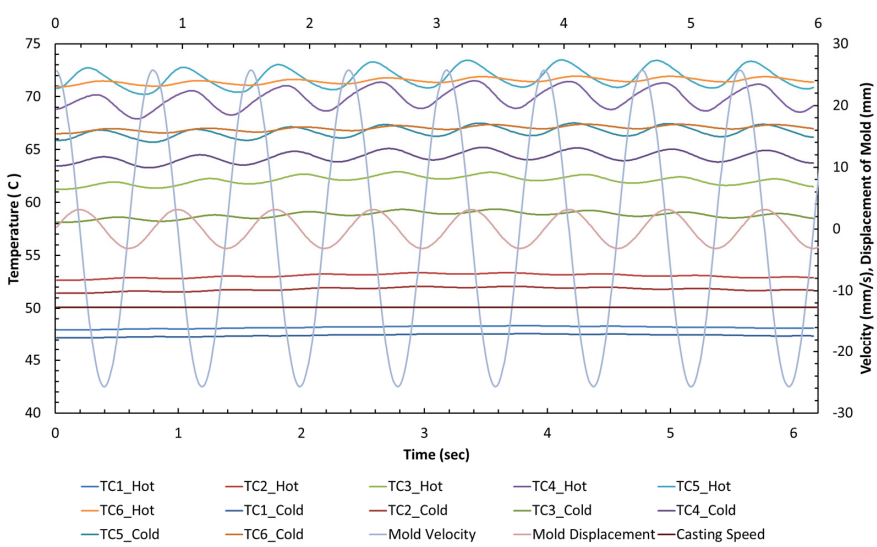
The term "Meniscus" for the model varies from the shell tip to the free surface (152 mm to 156.5mm) Based on this reasoning 152.5mm is taken to be meniscus to check the TC predictions

For the model, locations of the TCs are -

Meniscus = 152.5 mm

No	1	2	3	4	5	6
Distance from bottom (0,0) of domain (mm)	167.5	161.5	154.5	148.5	142.5	135.5

Model TC Predictions



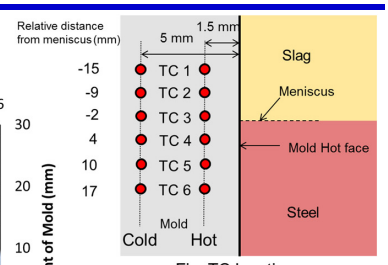


Fig: TC locations

TC Predictions: 1.5 mm from Mold Hot face

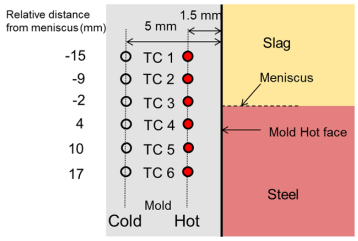
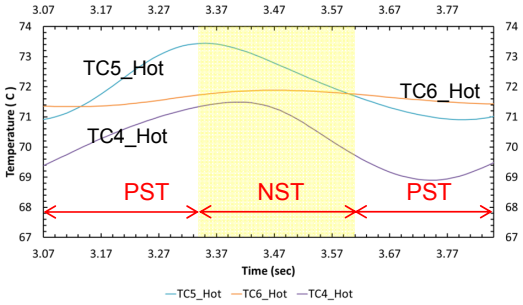
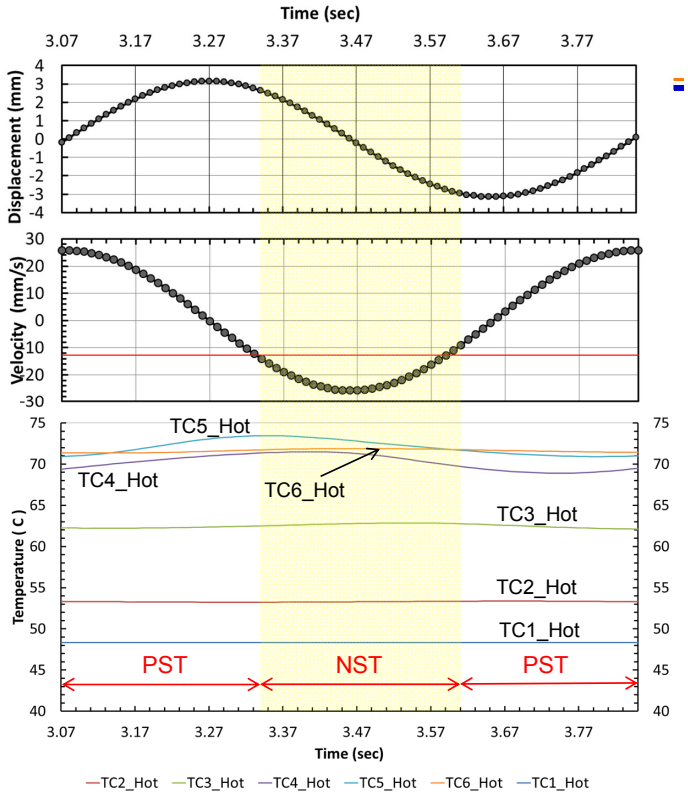


Fig: TC locations





TC Predictions: 5 mm from Mold Hot face

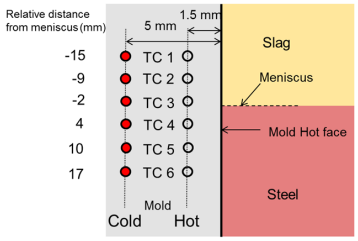
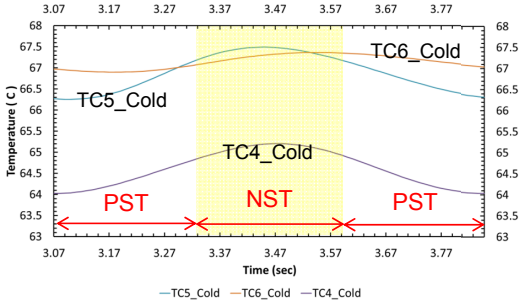
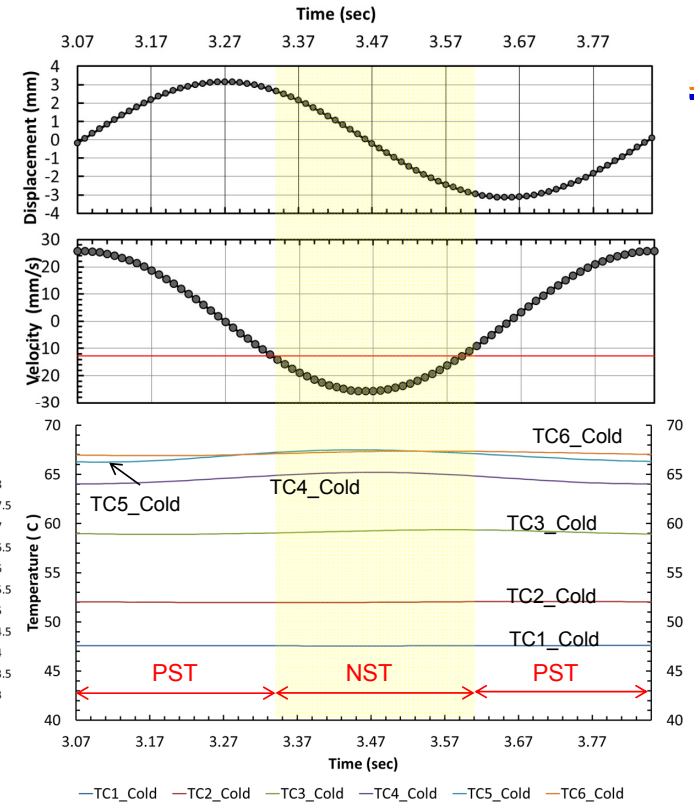


Fig: TC locations





Model Predictions vs. Badri Measurements (Trial 32): TC 3

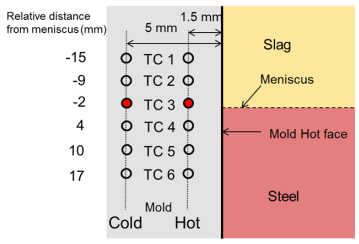
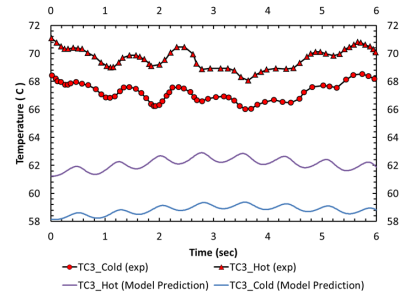
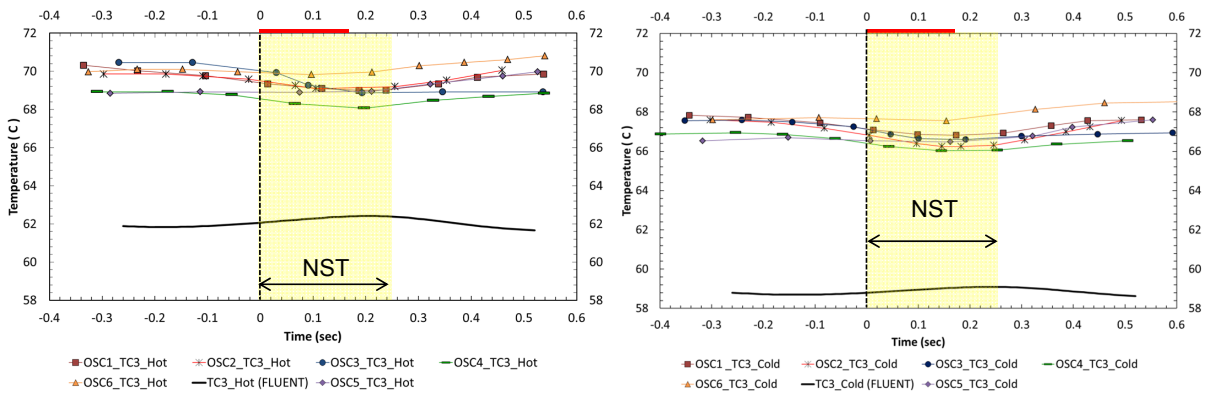


Fig: TC locations





Model Predictions vs. Badri Measurements (Trial 32): TC 4

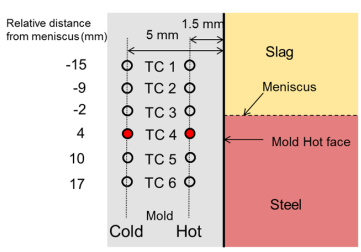
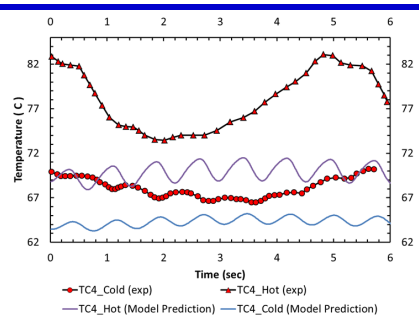
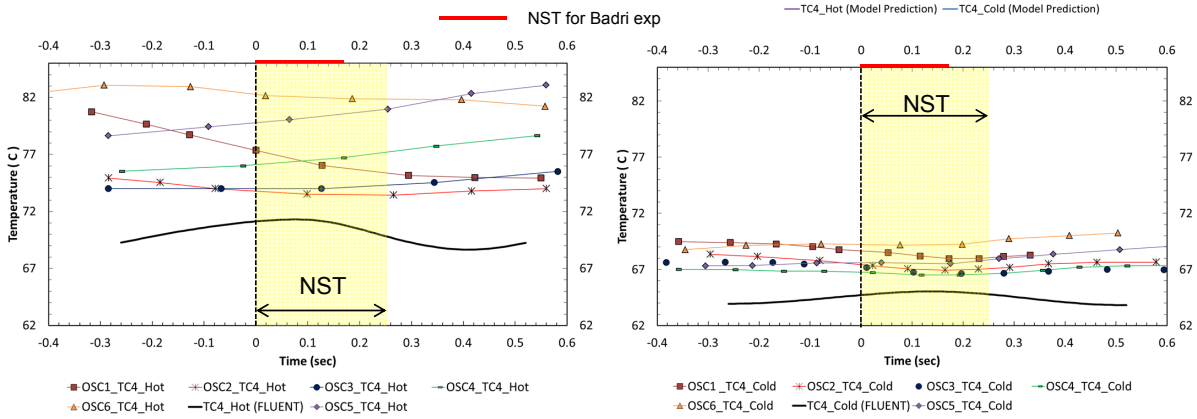


Fig: TC locations





Model Predictions vs. Badri Measurements (Trial 32): TC 5

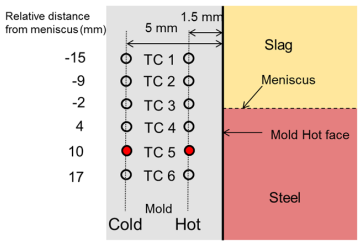
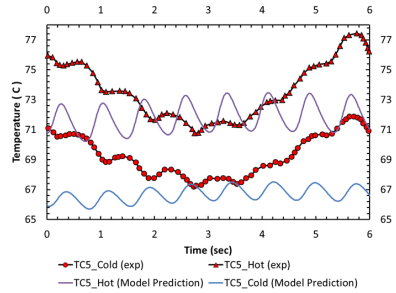
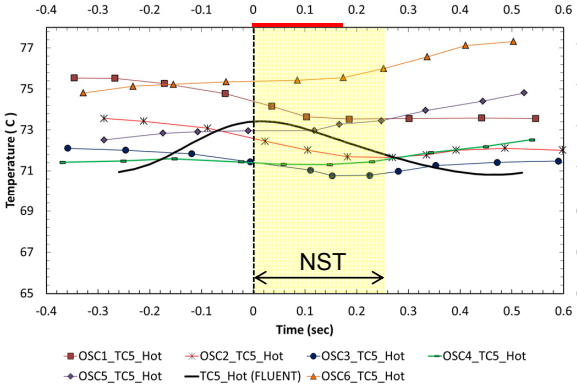
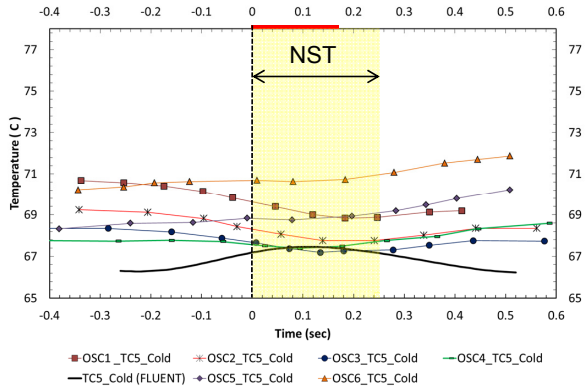


Fig: TC locations



NST for Badri exp





Model Predictions vs. Badri Measurements (Trial 32): TC 6

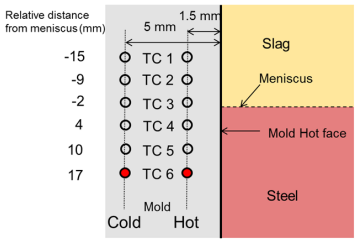
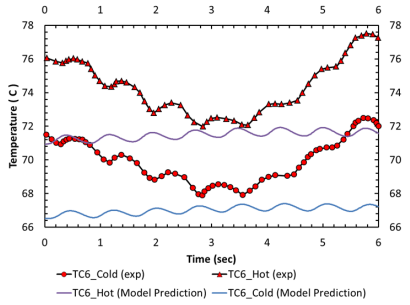
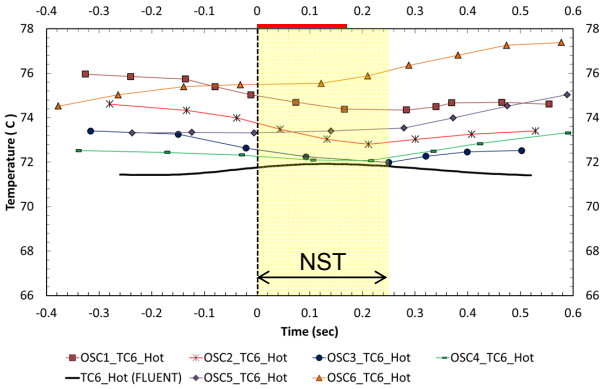
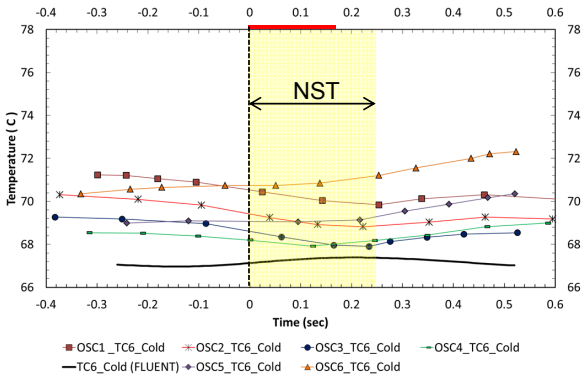


Fig: TC locations

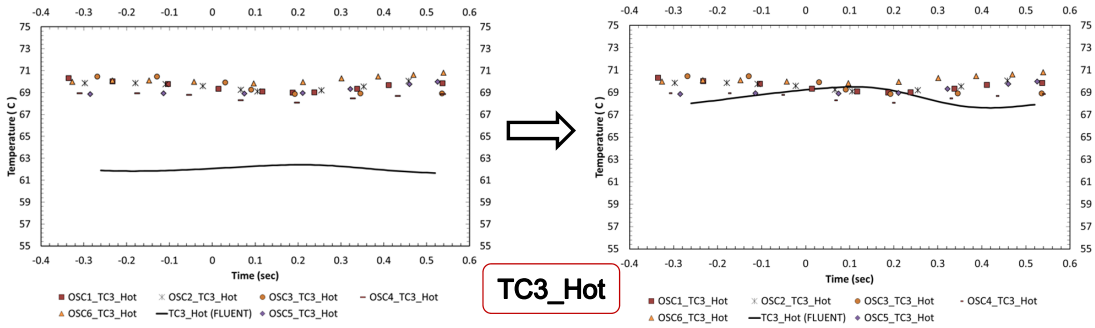


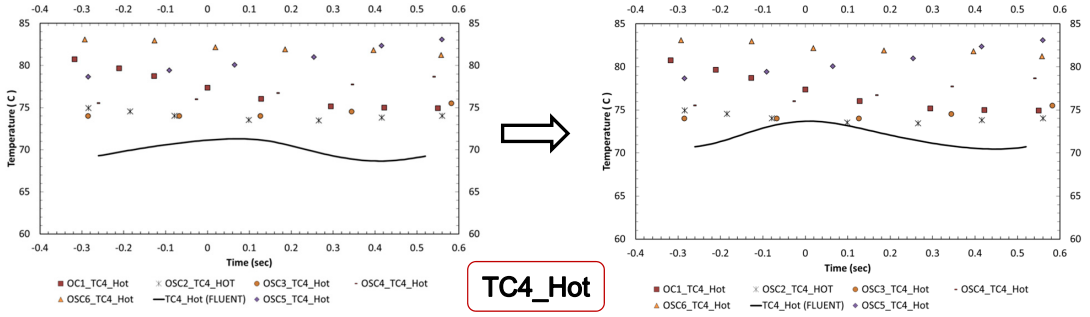
NST for Badri exp





Model Predictions: TC Location Shift (4 mm downwards)

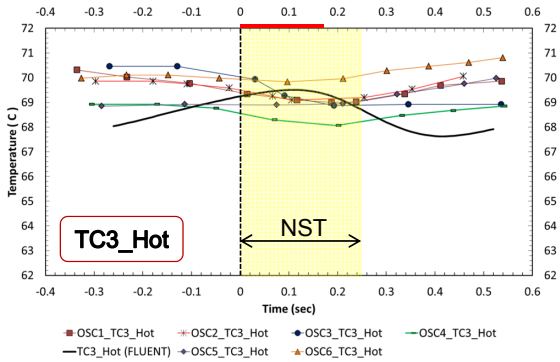


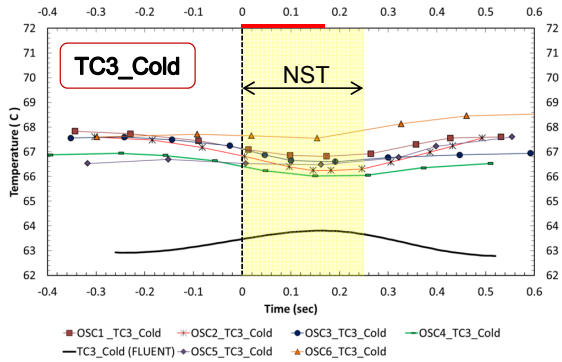


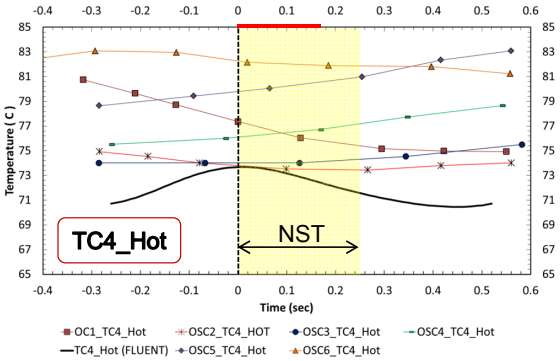
Predictions Before Shift

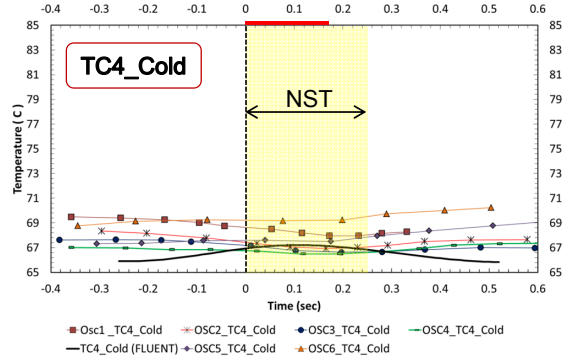
Predictions After Shift

Model Predictions vs. Badri Measurements (Trial 32):TC3, TC4 (after shifting)

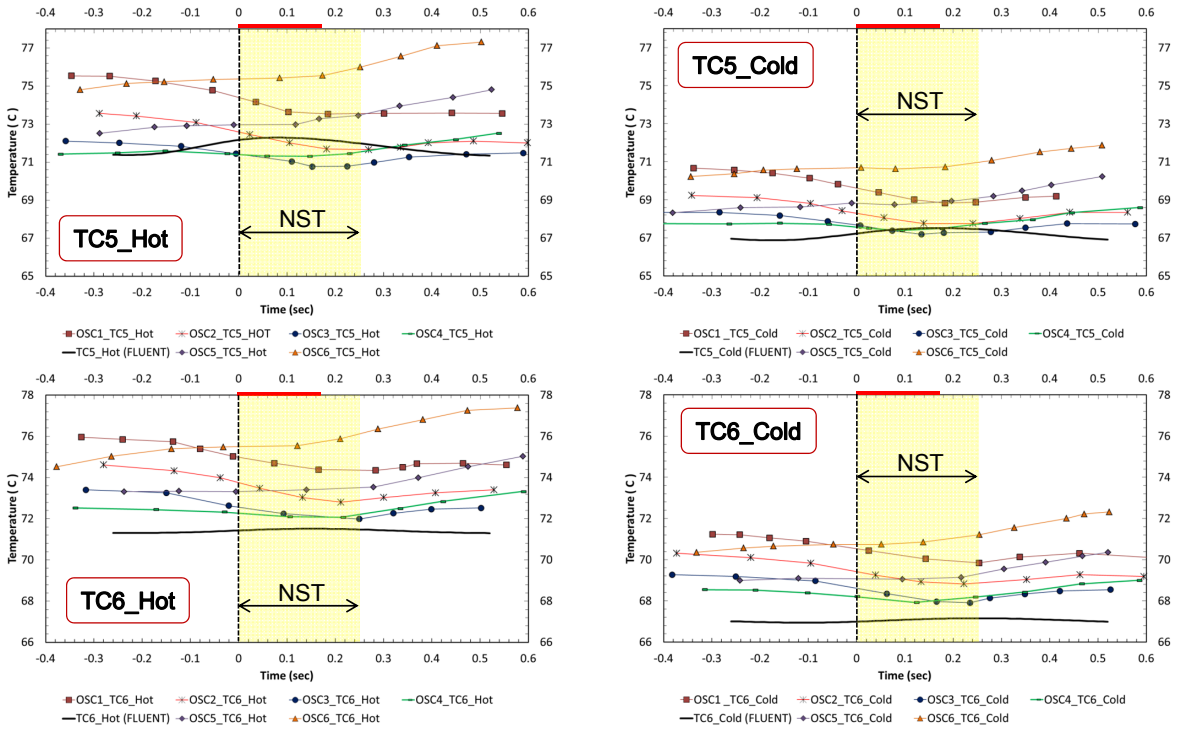








Model Predictions vs. Badri Measurements (Trial 32):TC5, TC6 (after shifting)



Model Predictions vs. Badri Measurements (Trial 30): TC 3

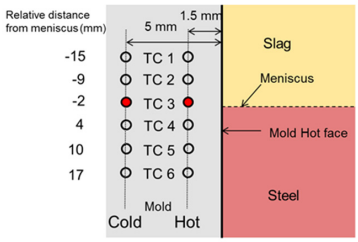


Fig: TC locations

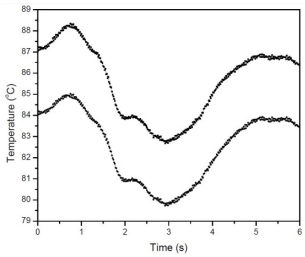
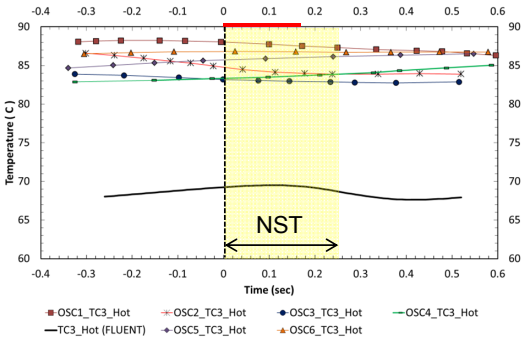


Fig:TC3 Measurements*

NST for Badri exp



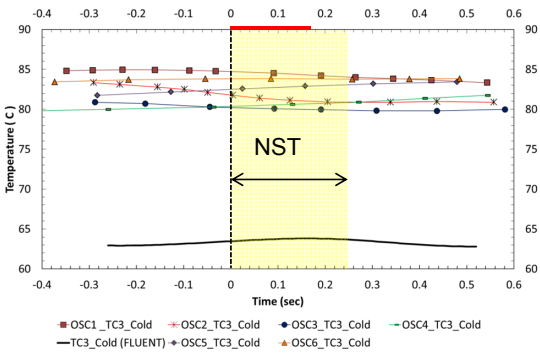


Fig: TC3 Predictions at vs Badri Measurements

*Badri Phd Thesis

Model Predictions vs. Badri Measurements (Trial 31): TC 3

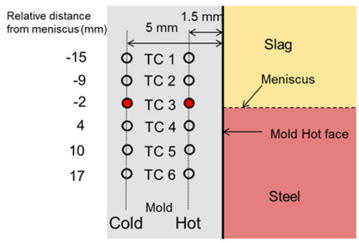


Fig: TC locations

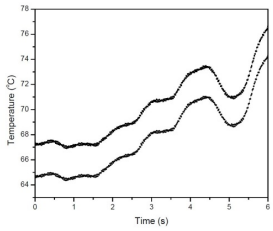
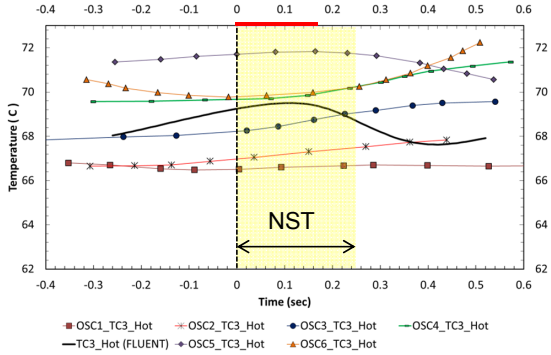


Fig:TC3 Measurements*

NST for Badri exp



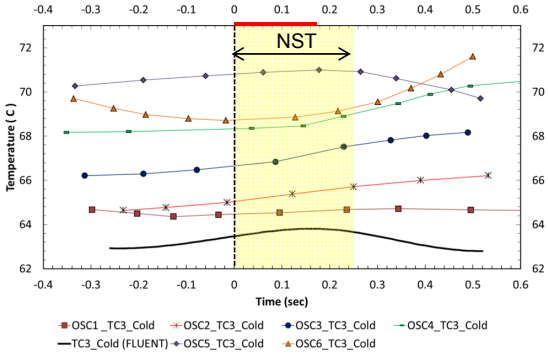


Fig: TC3 Predictions at vs Badri Measurements

*Badri Phd Thesis

Model Predictions vs. Badri Measurements (Trial 35): TC 3

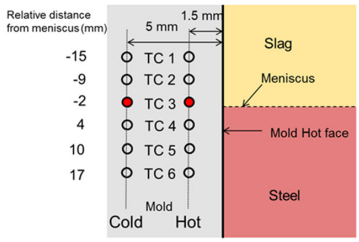


Fig: TC locations

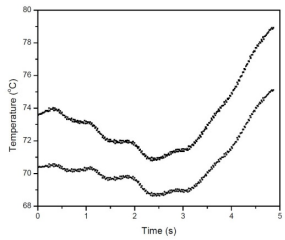
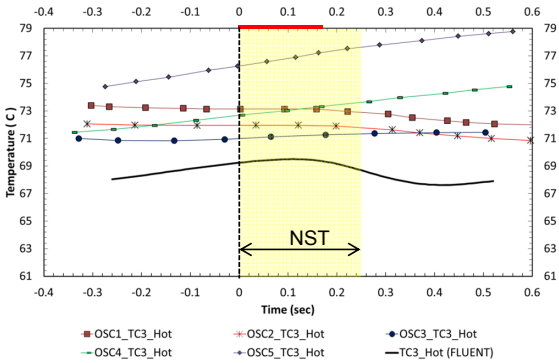


Fig:TC3 Measurements*

NST for Badri exp



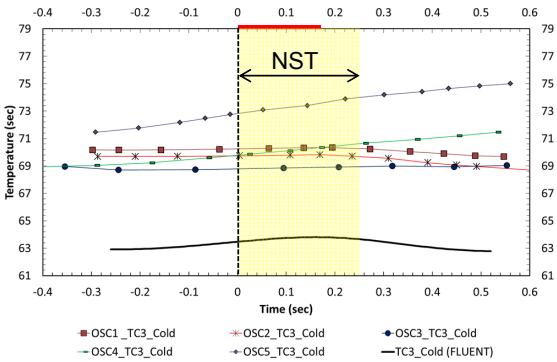


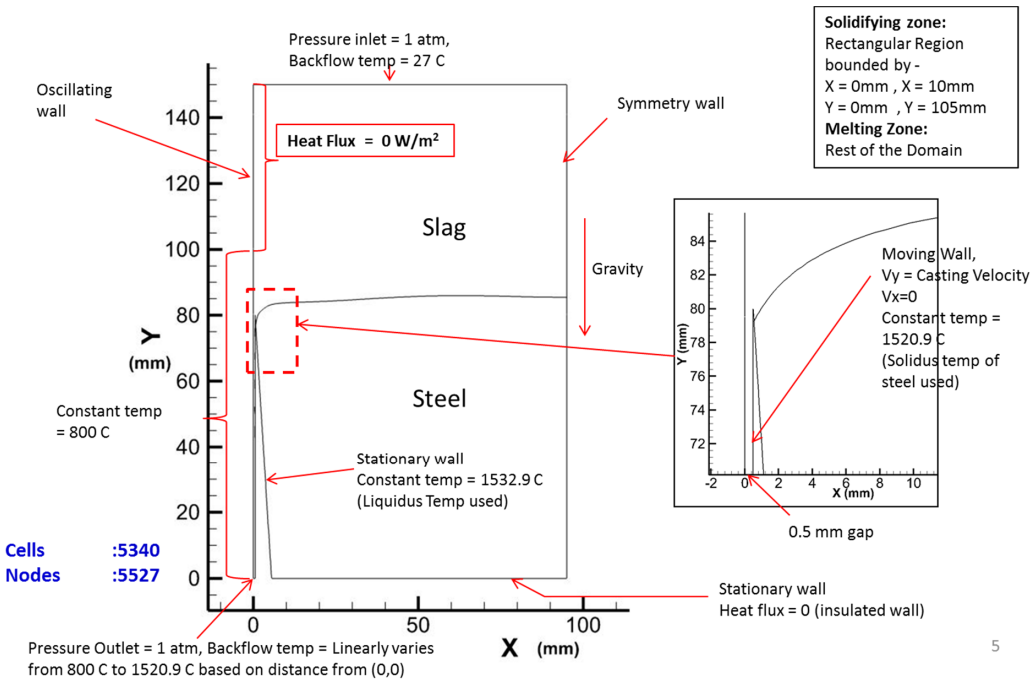
Fig: TC3 Predictions at vs Badri Measurements

*Badri Phd Thesis

Evaluation of Comparison (Predictions vs Badri Measurements)

- Many aspects agree well
  - Average temperatures and their variations at “hot” and “cold” thermocouples agree reasonably well
  - Thermocouples near meniscus show bigger variations during each oscillation cycle
  - Delay in response of colder thermocouple
- Discrepancies:
  - Predicted temperature variation is consistent:
    - increases during beginning of negative strip time (mold goes down into hotter region)
    - drops during end of negative strip time (“superheated” hot slag from steel shell inside is pushed into gap)
  - Badri measured temperatures vary between cycles:
    - Usually decrease during negative strip time; sometimes increase (but there is uncertainty in the timing of reading the figures so accurately)
    - Sometimes increase near end of negative time likely due to meniscus overflow causing high heat flux during negative strip, and a delay in TC response.
    - Sometimes continuously increase or decrease during entire cycle
- Conclusion: different behavior may occur for different situations

Slag Consumption Validation: Domain and Boundary Conditions



1 Cycle Temperature and Velocity Plot

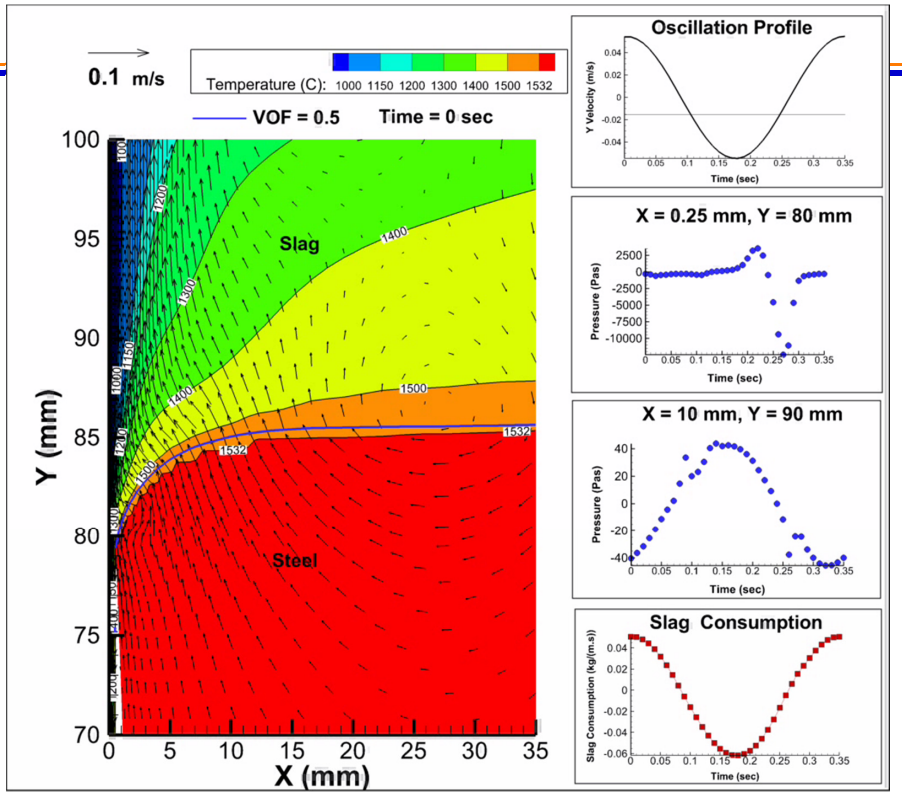
Casting Conditions:

Casting Velocity = 1.49 m/min

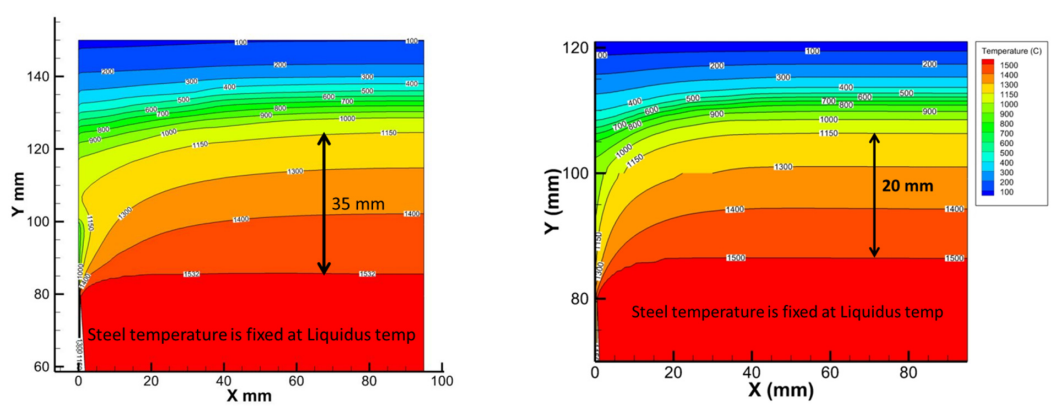
Stroke = 6.00 mm

Frequency = 173.9 cpm

Sinusoidal Oscillation (Modification Ratio = 0%)



Liquid Slag layer thickness above meniscus



(a) (b)

Figure : (a) 35 mm liquid slag pool with 65 mm initial powder slag layer, (b) 20 mm liquid slag pool with 35 mm initial powder slag layer

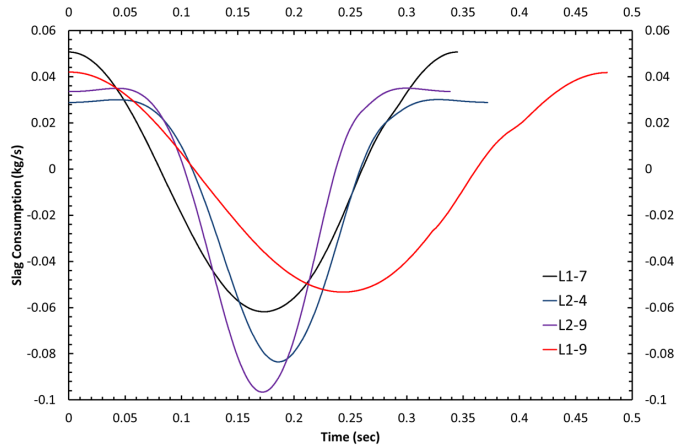
Model Validation with experimental data: Slag Consumption

- Model was applied to 4 different casting conditions for which the consumption data was available.
- Cases were taken from POSCO plant measurements in 2002 and 2003 from Shin*.
- For all cases the gap size was kept 0.5 mm.

Casting Conditions:

Case	Width (mm)	Casting Speed, Vc (m/min)	Stroke (mm)	Frequency, f (cpm)	Modification Ratio (%)
L1-7	1300	1.490	6.0	174	0
L1-9	1300	1.466	7.00	125.6	0
L2-4	1300	1.484	6.47	161.2	24
L2-9	1050	1.660	6.77	178.3	24

Model Predictions:



*Shin, Ho-Jung, S. H. Kim, B. G. Thomas, G. G. Lee, J. M. Park, and J. Sengupta, "Measurement and Prediction of Lubrication, Powder Consumption, and Oscillation Mark Profiles in Ultra-low Carbon Steel Slabs," ISIJ International, 46:11, 1635-1644, 2006.

Slag Consumption: Experimental Vs. Predicted

Table : Casting conditions, Measured and Predicted Slag Consumption*

Case	Width (mm)	Casting Speed, Vc (m/min)	Stroke (mm)	Frequency, f (cpm)	Modification Ratio (%)	Negative Strip time (s)	Positive Strip time (s)	Slag Consumption measured, Q (kg/m^2)	Slag Consumption measured, (kg/ms)	Slag Consumption predicted (kg/ms)	Error (%)
L1-7	1300	1.490	6.0	174	0	0.121	0.224	0.230	0.0057	0.0052	-8.8%
L1-9	1300	1.466	7.00	125.6	0	0.154	0.324	0.208	0.0051	0.0051	0%
L2-4	1300	1.484	6.47	161.2	24	0.106	0.267	0.238	0.0059	0.0053	-10.2%
L2-9	1050	1.660	6.77	178.3	24	0.097	0.240	0.194	0.0054	0.006	11.1%

Model consumption predictions agree well with plant measurements, considering possible differences in overflow details and lack of oscillation mark consumption

*Shin, Ho-Jung, S. H. Kim, B. G. Thomas, G. G. Lee, J. M. Park, and J. Sengupta, "Measurement and Prediction of Lubrication, Powder Consumption, and Oscillation Mark Profiles in Ultra-low Carbon Steel Slabs," ISIJ International, 46:11, 1635-1644, 2006.

Parametric Studies

A parametric study was done on slag consumption by varying 4 casting conditions.

- Casting Speed
- Stroke
- Frequency
- Modification Ratio

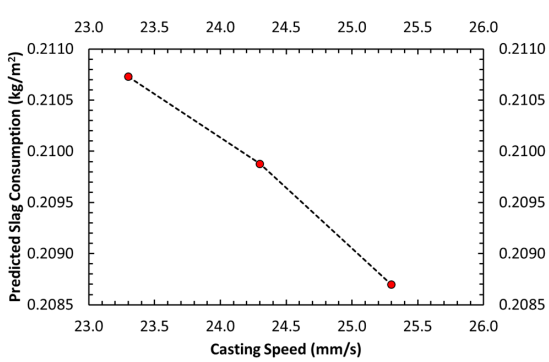
In all cases

- the gap size is kept 0.5 mm
- an initial interface between liquid slag and steel is prescribed with 6.5 mm free surface vertical distance from the shell tip.

Parametric Studies: Casting Speed

Casting Speed:

Casting Speed (Variable) (mm/s)	Stroke (mm)	Frequency (cpm)	Modification Ratio (%)	Negative strip time (sec)	Positive strip time (sec)	Predicted slag consumption (kg/(m.s))	**Predicted slag consumption (kg/m²)**
23.3	7.00	125.6	0	0.158	0.319	0.00491	**0.2107**
24.3	7.00	125.6	0	0.154	0.324	0.00510	**0.2099**
25.3	7.00	125.6	0	0.150	0.327	0.00528	**0.2087**



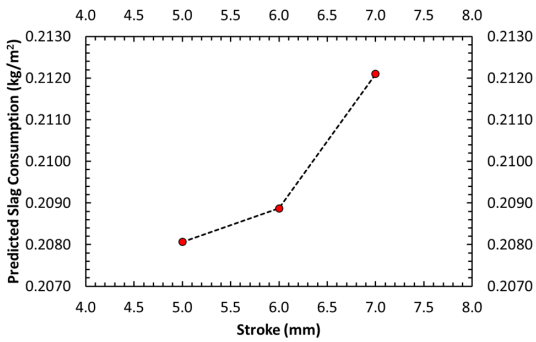
- Slag consumption per unit area decreases with increase of Casting speed
- Matches plant measurements*
- **8.6%** increase in casting speed decreases the consumption by **1%**

*Shin, Ho-Jung, S. H. Kim, B. G. Thomas, G. G. Lee, J. M. Park, and J. Sengupta, "Measurement and Prediction of Lubrication, Powder Consumption, and Oscillation Mark Profiles in Ultra-low Carbon Steel Slabs," ISIJ International, 46:11, 1635-1644, 2006.

Parametric Studies: Stroke

Stroke:

Casting Speed (mm/s)	**Stroke (Variable) (mm)**	Frequency (cpm)	Modification Ratio (%)	Negative strip time (sec)	Positive strip time (sec)	Predicted slag consumption (kg/(m.s))	**Predicted slag consumption (kg/m²)**
24.8	**5.00**	174.0	0	0.109	0.236	0.00516	**0.2081**
24.8	**6.00**	174.0	0	0.121	0.224	0.00518	**0.2089**
24.8	**7.00**	174.0	0	0.129	0.216	0.00526	**0.2121**



- Higher slag consumption per unit are is predicted with increasing stroke length
- This agrees to the works of Tsutsumi*
- **40%** increase in casting stroke increases slag consumption by **2%**.

*K. Tsutsumi, H. Murakami, S. Nishioka, M. Tada, M. Nakada and M. Komatsu: Tetsu-to-Hagané, 84 (1998), 617.

Parametric Studies: Frequency

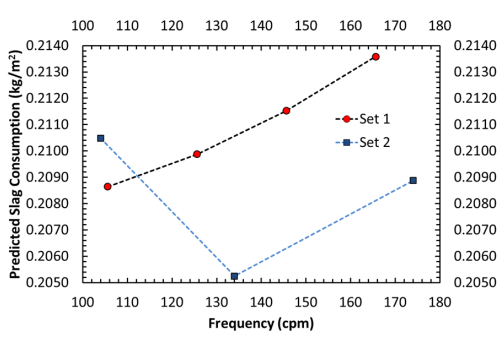
Frequency:

Set 1:

Casting Speed (mm/s)	Stroke (Variable) (mm)	**Frequency (cpm)**	Modification Ratio (%)	Negative strip time (sec)	Positive strip time (sec)	Predicted slag consumption (kg/(m.s))	**Predicted slag consumption (kg/m²)**	**Predicted slag consumption (kg/m.cycle)**
24.3	7.00	**105.6**	0	0.154	0.324	0.00507	**0.2086**	**0.0029**
24.3	7.00	**125.6**	0	0.161	0.408	0.00510	**0.2099**	**0.0024**
24.3	7.00	**145.6**	0	0.144	0.268	0.00514	**0.2115**	**0.0021**
24.3	7.00	**165.6**	0	0.133	0.229	0.00519	**0.2136**	**0.0019**

Set 2:

Casting Speed (mm/s)	Stroke (Variable) (mm)	**Frequency (cpm)**	Modification Ratio (%)	Negative strip time (sec)	Positive strip time (sec)	Predicted slag consumption (kg/(m.s))	**Predicted slag consumption (kg/m²)**	**Predicted slag consumption (kg/m.cycle)**
24.8	6.00	**104.0**	0	0.130	0.447	0.00522	**0.2105**	**0.0030**
24.8	6.00	**134.0**	0	0.134	0.314	0.00509	**0.2052**	**0.0023**
24.8	6.00	**174.0**	0	0.121	0.224	0.00518	**0.2089**	**0.0018**



~62% increase in frequency causes slag consumption (kg/m²) to:
- sometimes increases by **~2%**
- sometimes decreases by **~1%**

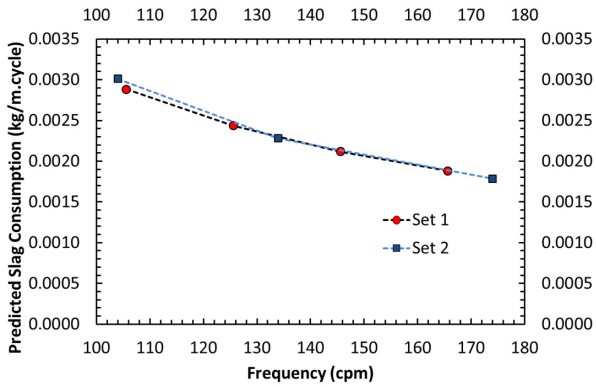
Parametric Studies: Frequency

Table 3. *Reported effect of frequency (f) and stroke length (S) on increasing powder consumption (↑)*

	Kwon [22]	Wolf [26]	Tsutsumi [8]	Nakato [28]	Maeda [21]	Kitagawa [29]
f	↓	↓	↓	↓	↑	↑

*Rajil Saraswat, A. B. Fox, K. C. Mills, P. D. Lee and B. Deo, Scandinavian Journal of Metallurgy 2004; 33: 85–91

- Empirical relations reported by Saraswat* show both increasing and decreasing trend of slag consumption per unit (kg/m^2) with increase of frequency.



Increasing frequency by **~62%** causes predicted consumption per cycle decrease by **~35%.**

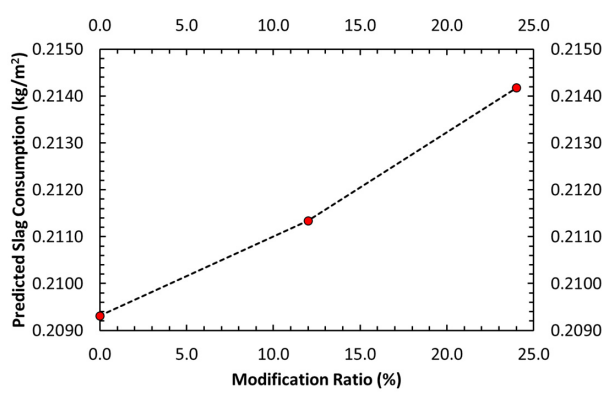
- Shin's** equation for predicting slag consumption (based on plant measurements) predicts consumption per cycle (kg/m.cycle) decreases with increasing frequency

**Shin, Ho-Jung, S. H. Kim, B. G. Thomas, G. G. Lee, J. M. Park, and J. Sengupta," ISIJ International, 46:11, 1635-1644, 2006.

Parametric Studies: Modification Ratio

Modification Ratio:

Casting Speed (mm/s)	Stroke (Variable) (mm)	Frequency (cpm)	**Modification Ratio (%)**	Negative strip time (sec)	Positive strip time (sec)	Predicted slag consumption (kg/(m.s))	**Predicted slag consumption (kg/m^2)**
24.7	6.47	155.0	**0**	0.109	0.278	0.00517	**0.2093**
24.7	6.47	155.0	**12**	0.109	0.278	0.00522	**0.2113**
24.7	6.47	155.0	**24**	0.109	0.278	0.00529	**0.2142**



- Model predicts increased consumption with increasing Modification Ratio
- Suzuki* observed this behavior in experiments
- Sinusoidal to non-sinusoidal (**24%**) causes an increase of **2.3%** in slag consumption

*M. Suzuki, H. Mizukami, T. Kitagawa, K. Kawakami, S. Uchida and M. Komatsu: ISIJ Int., 31 (1991), 254.

Conclusions

- A transient thermo-fluid model is developed to study transient heat transfer and slag consumption in the meniscus region
- Model applied to Badri experiment reveals insight into transient behavior.
  - Steady-state model temperatures and heat flux were calibrated to match Badri experiment
  - Thermocouples near meniscus show bigger variations during each oscillation cycle
  - Model predicts temperature increase at beginning of negative strip, dropping later at different times for different positions
  - Wide variation in transient behavior is present the measured temperatures for the same grade of steels.
  - The meniscus position is important for comparing model predictions with measured values.
- Consumption prediction for realistic casting conditions matches closely with plant measurements. However, slag consumption measurements in the plant includes a lot of variance depending on how it is measured.
- Parametric studies shows model predicted effect of changing casting conditions on slag consumptions are in excellent agreement with plant observations.
- For accurate modeling of the phenomena at the meniscus, transient solidification and better measurements are essential.

Future Work

- Using solidification model (FLUENT) for prediction of shell growth rather than fixing it. (This model has been verified with analytical solution for implementation)
- Defining solidification and melting zone of slag based on their temperature history.
- Apply model for different casting conditions to predict effects of each casting parameter.
- Characterization of shell growth and oscillation mark formation under the effect of oscillating mold.

Acknowledgments

- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Magnesita Refractories, Nippon Steel & Sumitomo Metal Corp., Nucor Steel, Postech/ Posco, Severstal, SSAB, Tata Steel, ANSYS/ Fluent)
- A. W. Cramb for providing PhD Thesis of Adam Badri