CCC Annual Report

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Effect of SEN Conductivity on Meniscus Solidification

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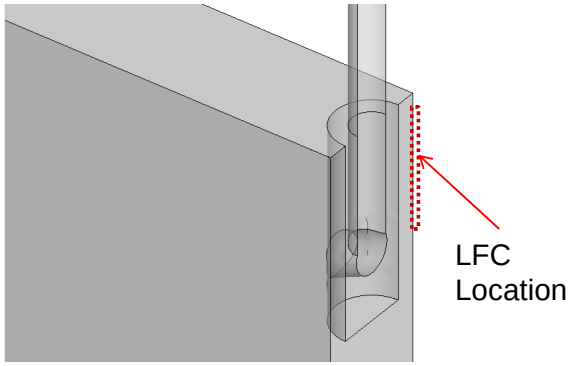
Background & Objective

- Plant data shows less Longitudinal Facial Cracks with high conductivity nozzle
- Investigate heat transfer and other mechanisms related to meniscus solidification and defects such as LFC

SEN Material	ZG806H	ZG797H
Conductivity (W/mK)	6.98	15.2
Erosion rate (mm/min)	0.007	0.015
Density (kg/m^3)	3840	3550
Composition ($ZrO_2\%$)	82	75
Composition (C %)	13	20

Magnesita Refratarios S.A.



Possible Mechanisms

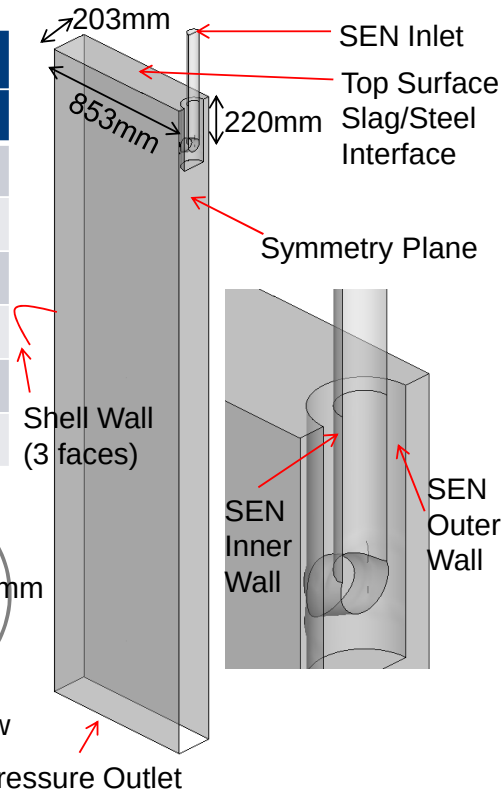
- SEN conductivity changes heat transfer in molten steel, changing meniscus heat flow and meniscus solidification.
- SEN conductivity changes heat transfer, and thus also flow, in slag layer, leading to,
  a) changes in meniscus solidification, or
  b) changes in slag consumption infiltration into the gap
- Nozzle refractory wall dissolution changes might lead to changes to slag composition, slag viscosity, thereby also slag flow and heat transfer.

Description of Models

- A 3D k-ε turbulent fluid flow – heat transfer model of the molten steel pool.
- A 2D thermal-flow model of the slag layer near SEN.
- A 2D thermal-flow species (ZrO_2) diffusion model of the slag layer near SEN

3D Domain & Boundary Conditions

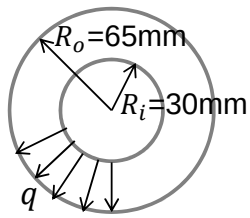
	High Superheat		Low Superheat	
4 Cases	**High k**	**Low k**	**High k**	**Low k**
SEN Inlet Temp(K)	1854	1854	1829	1829
Superheat (K)	49.13	49.13	24.13	24.13
Outer Wall h $(^{W}/_{m^2K})$	302.4	138.9	302.4	138.9
Outer Wall T_{amb} (K)	1852.8	1853.1	1828.3	1828.3
Inner Wall h $(^{W}/_{m^2K})$	655.3	300.9	655.3	300.9
Inner Wall T_{amb} (K)	1827.0	1826.5	1815.3	1815.3



SEN Wall:
Convective boundary condition (see chart)
No mesh inside the wall (use B.C. instead)

Top Surface: No Slip Wall
$h = 244 W/m^2K$
$T_{amb} = 1400K$

Shell: v=23.3mm/s $T = T_{liquidus} = 1804.87K$



SEN Top View

SEN Wall & Top Surface Boundary Condition

Top Surface

- Models the convection inside molten slag layer
- Free stream temperature set to be 1400K
- Heat transfer coefficient is acquired from the 2D model presented in this work:
  - Average heat flux at the bottom of the 2D model domain (slag/steel interface) $\approx 10^5\ W/m^2$
  - $\Delta T \approx 1810K - 1400K = 410K$
  - $h = \frac{q}{\Delta T} \approx 244\ W/m^2K$

SEN Wall

- h: Heat resistor built into the boundary condition, to model the heat conduction inside the wall, without a mesh
- Define:

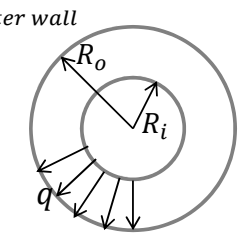
$$\begin{cases} h_i = q/(\Delta T \times 2\pi R_i) \\ h_o = q/(\Delta T \times 2\pi R_o) \end{cases}$$

$$\Delta T = T_{inner\ wall} - T_{outer\ wall}$$

- Analytical Solution:

$$q = 2\pi k \Delta T / ln(R_o/R_i)$$

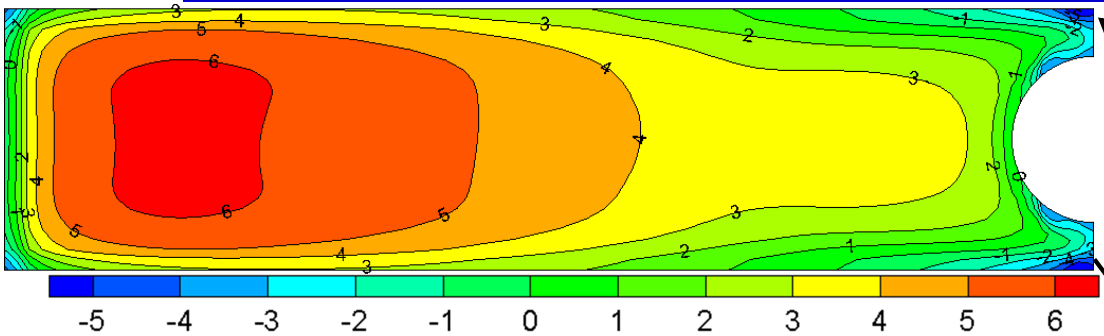
$$\begin{cases} h_i = k/\left(R_i \times ln\frac{R_o}{R_i}\right) \\ h_o = k/\left(R_o \times ln\frac{R_o}{R_i}\right) \end{cases}$$



- Free stream Temp acquired by iteratively improving an initial guess between the liquidus Temp & Inlet Temp

$$\begin{cases} T_{amb}\ for\ inner\ wall = T_{outer\ wall} \\ T_{amb}\ for\ outer\ wall = T_{inner\ wall} \end{cases}$$

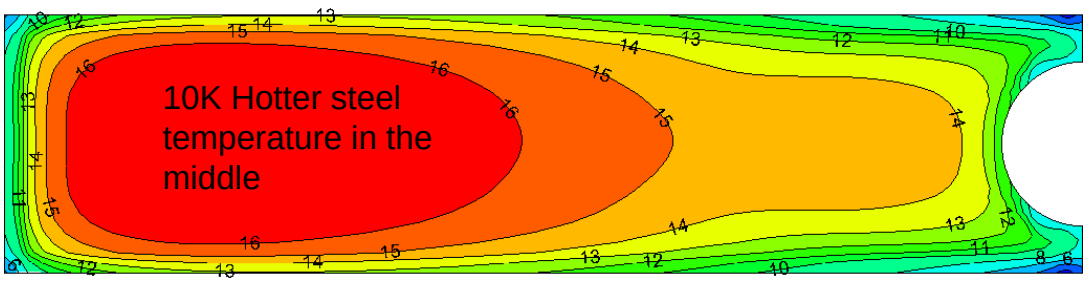
Effect of Initial Superheat on Top Surface Temperature Distribution



Superheat (K): Low Initial Superheat Condition (24K)

Negative superheat: meniscus freezing

Meniscus Temp increase $\approx 7K$



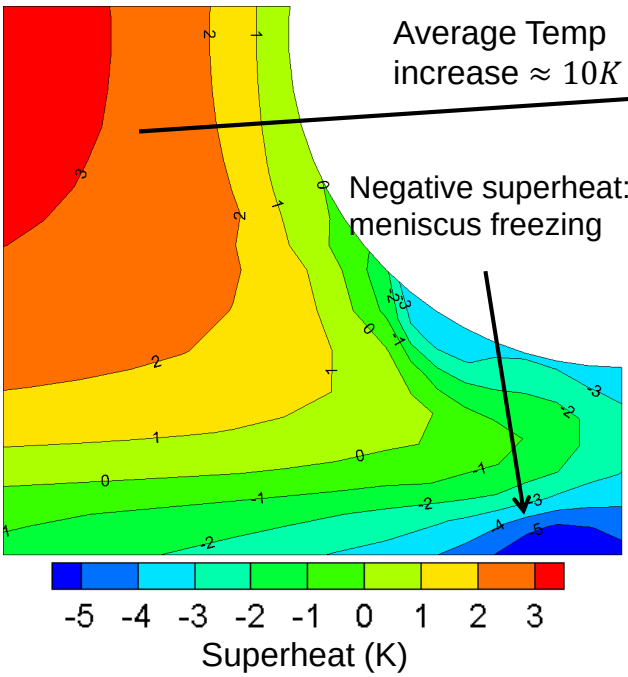
Superheat (K): High Initial Superheat Condition (49K)

Zoomed in at SEN & Wide Face

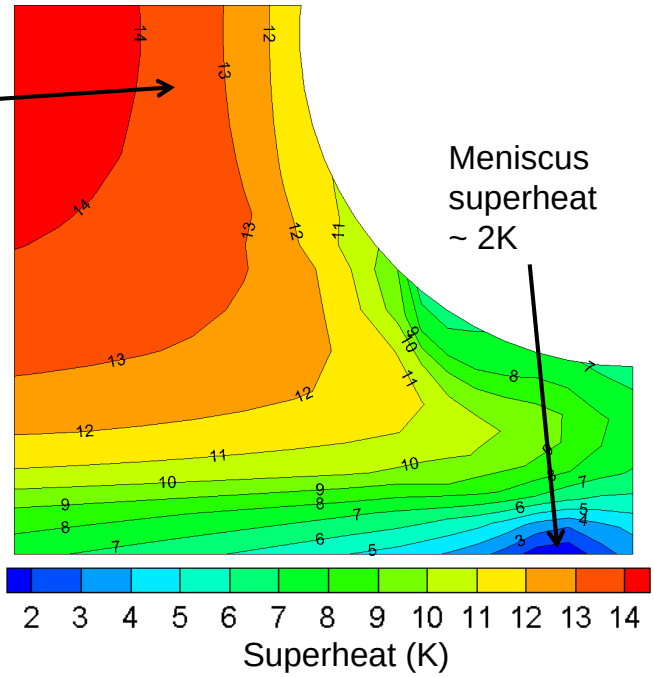
Average Temp increase $\approx 10K$

Negative superheat: meniscus freezing

Meniscus superheat ~ 2K

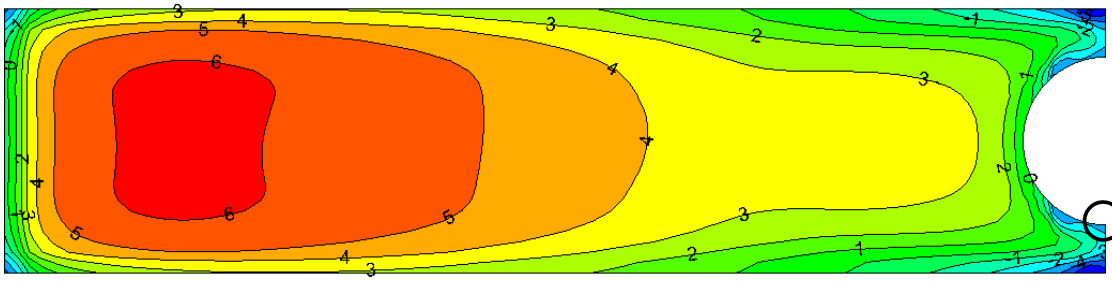


Low Initial Superheat Condition (24K)



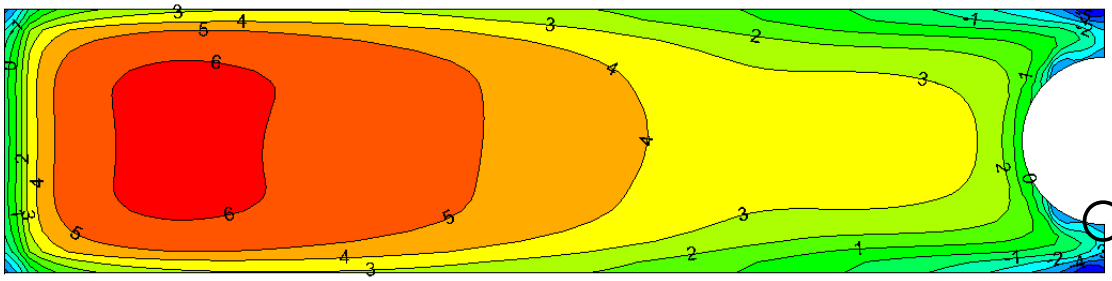
High Initial Superheat Condition (49K)

Effect of SEN k on Top Surface Superheat distribution



Higher SEN k causes negligible Temp increase

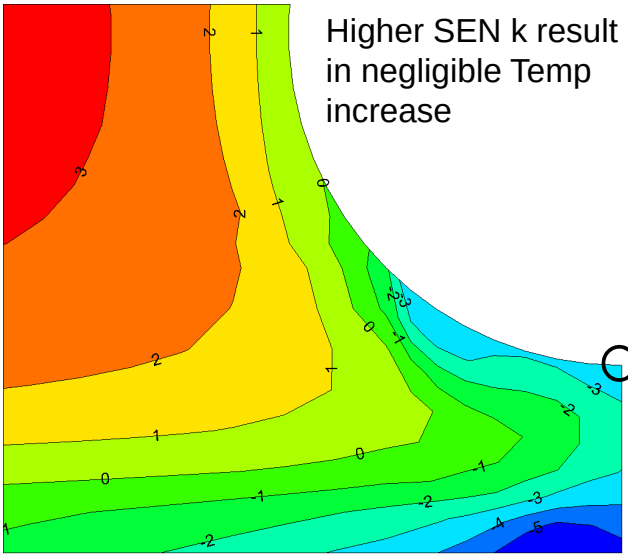
Low SEN Conductivity



Biggest increase: 0.16K

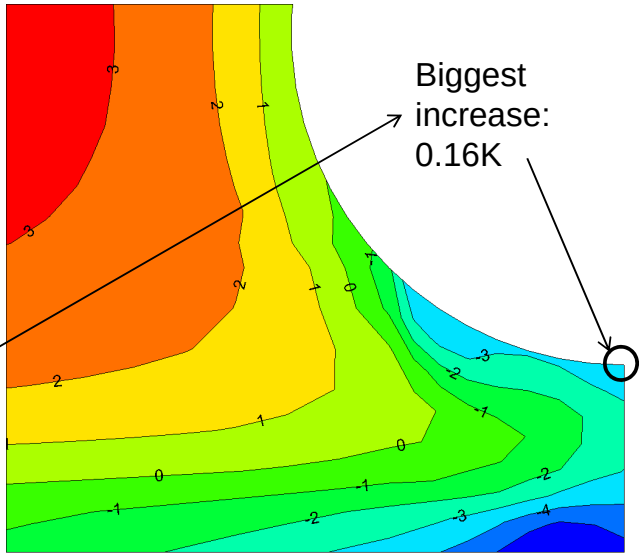
High SEN Conductivity

Zoomed in at SEN & Wide Face



Higher SEN k result in negligible Temp increase

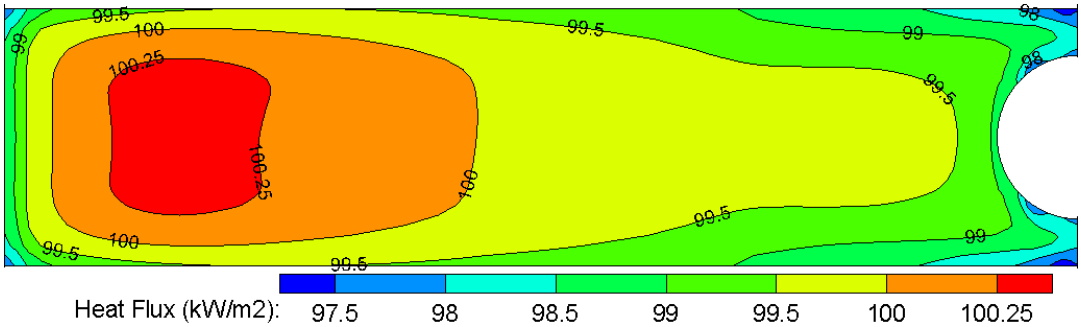
Low SEN Conductivity



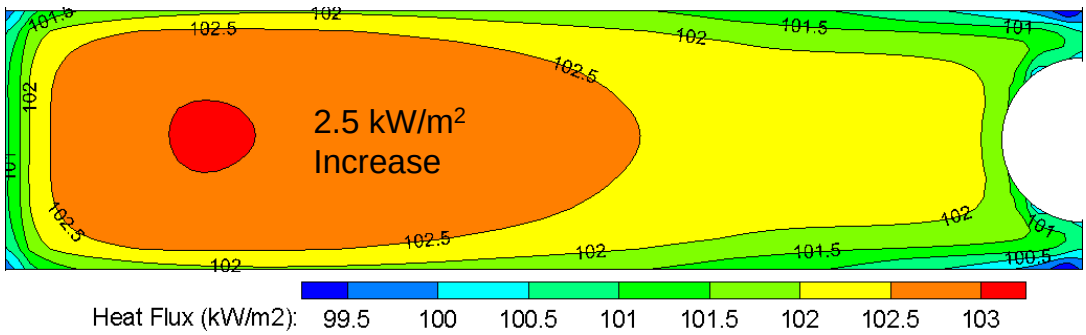
Biggest increase: 0.16K

High SEN Conductivity

Effects of Initial Superheat on Top Surface Heat Flux

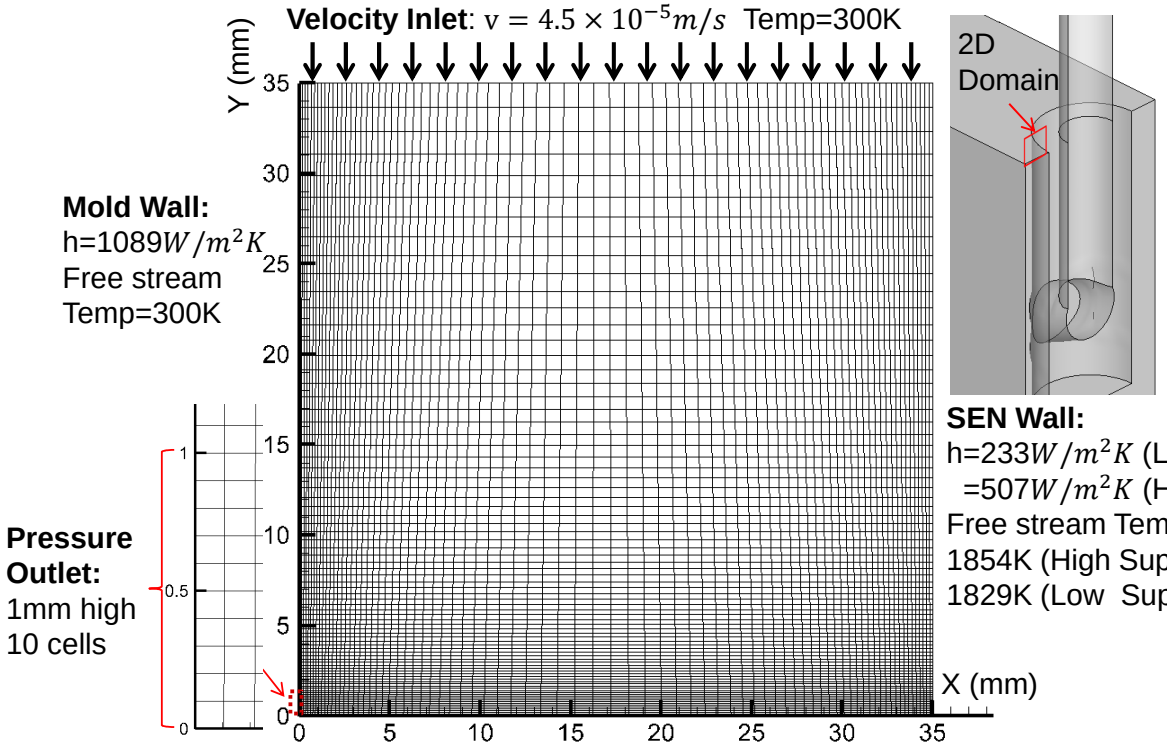


Low Initial Superheat Condition (24K)



High Initial Superheat Condition (49K)

2D Slag-Layer Domain, Mesh & Boundary Conditions



Slag/Steel Interface (Wall): Temp/Marangoni Profile from 3D simulation

Calculation of Marangoni Effect

Marangoni Shear : $\sigma = \frac{\partial \gamma}{\partial T} \cdot \frac{\partial T}{\partial x}$

$\frac{\partial \gamma}{\partial T}$ ~Tension gradient w.r.t. Temp

$\frac{\partial T}{\partial x}$ ~Temp gradient along surface

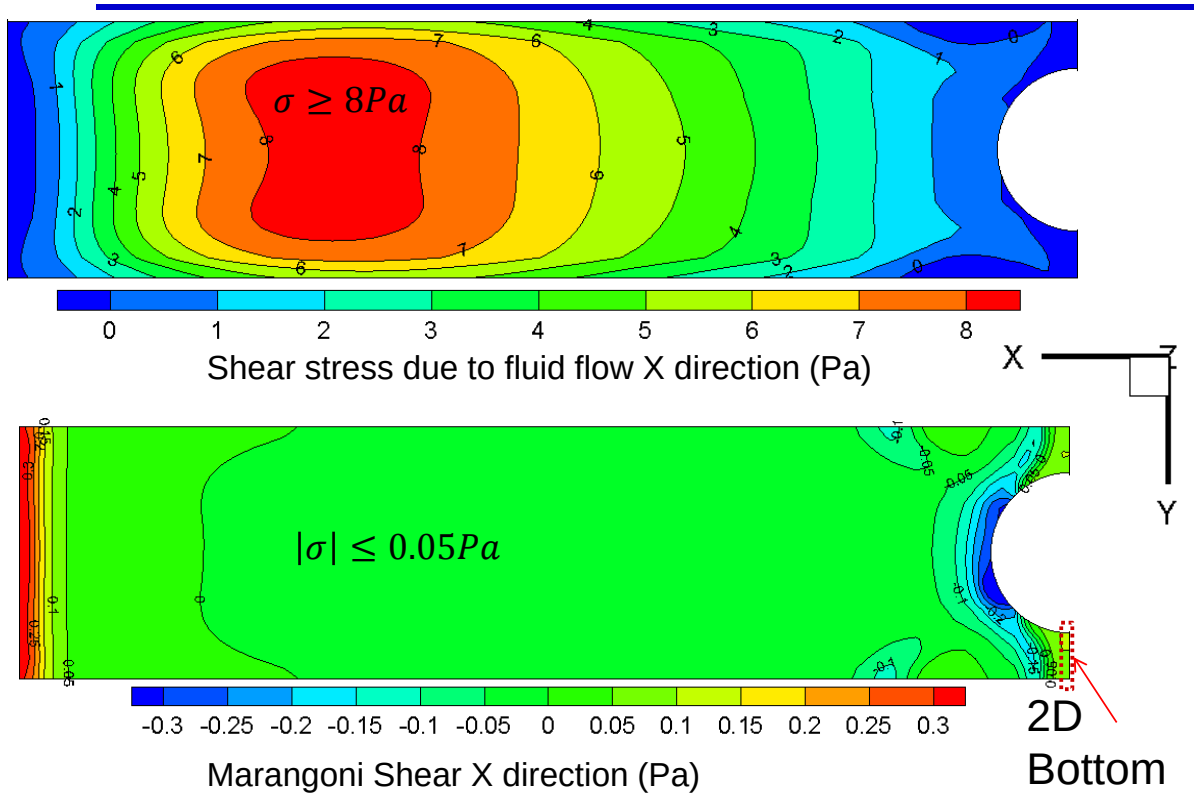
Temperature (℃)	1550	1600
Tension (N/m)	1.418	1.376

L MUHMOOD, N. VISWANATHAN, S SEETHARAMAN, The Minerals, Metals & Materials Society and ASM International 2011

$$\frac{\partial \gamma}{\partial T} = \frac{1376 - 1418}{1600 - 1550} = 8.38 \times 10^{-4} N/mK$$

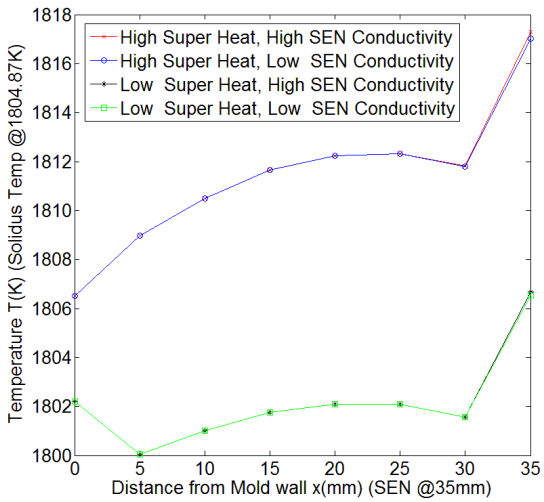
- Shear stress acting surface due to nonuniform surface tension, due to temperature or composition gradients
- Surface tension decreases with Temp
- Larger Marangoni effect where Temp gradients are larger

3D Top Face Compare: fluid-flow Shear & Marangoni Shear

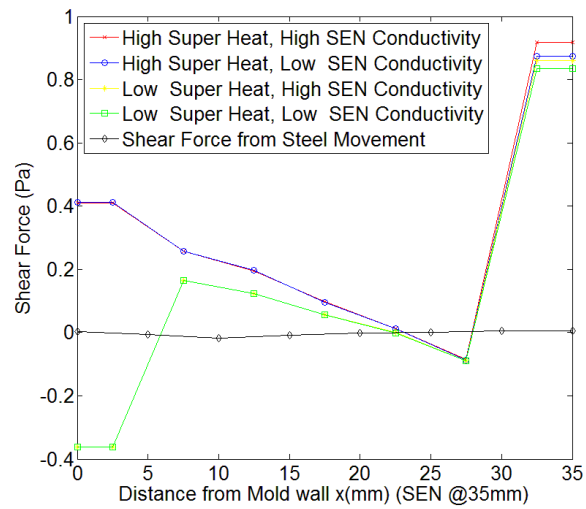


Temp & Shear Profile at 2D Bottom Interface input condition

(from 3D model)



Temp Distribution Profile

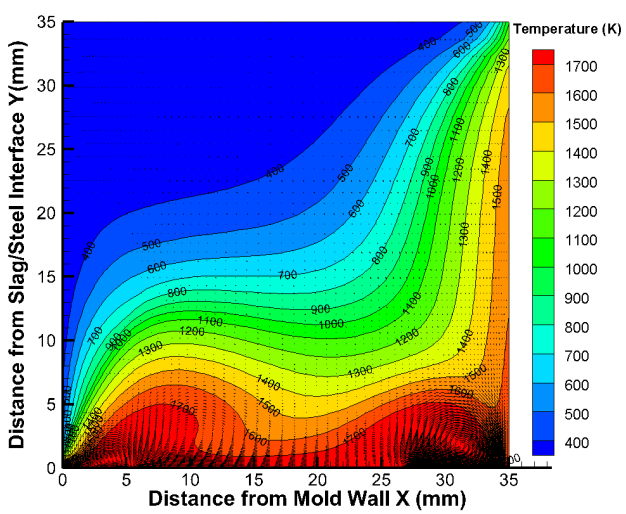


Shear Distribution Profile

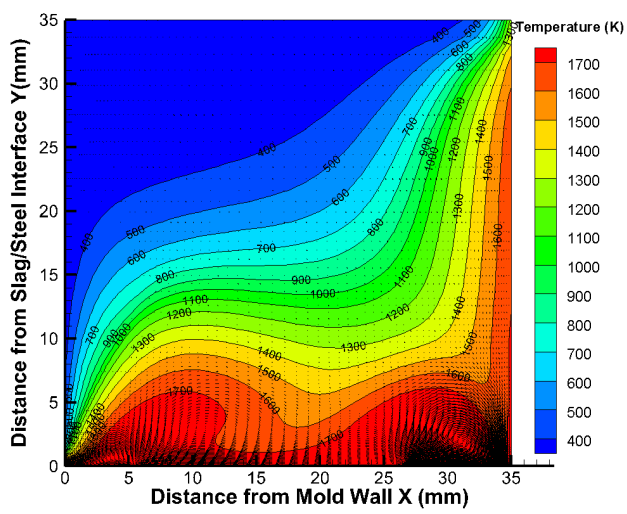
$$\begin{cases} Fluid - Flow\ Shear: on\ the\ magnitude\ of\ 0.01Pa \\ Marangoni\ Shear: on\ the\ magnitude\ of\ 0.1Pa \end{cases}$$

2D Model Results: Flow & Temp.

(24K - Low Initial Superheat)



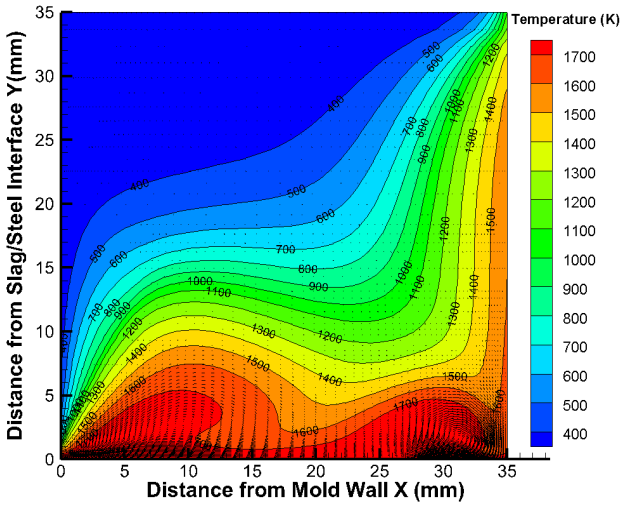
Low SEN conductivity



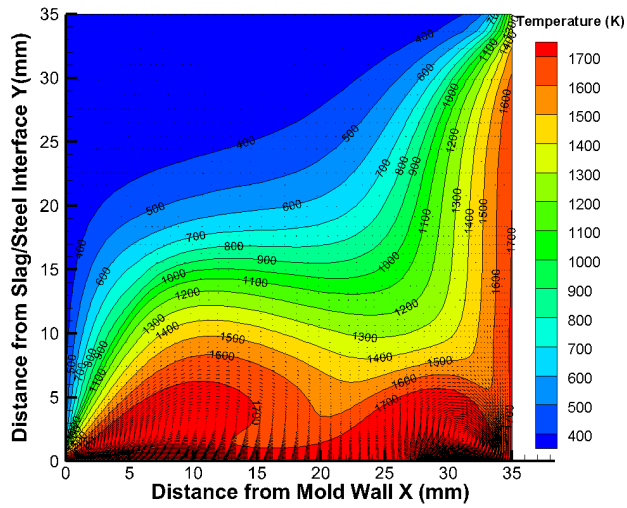
High SEN conductivity

2D Model Results: Flow &Temp.

(49K - High Initial Superheat)

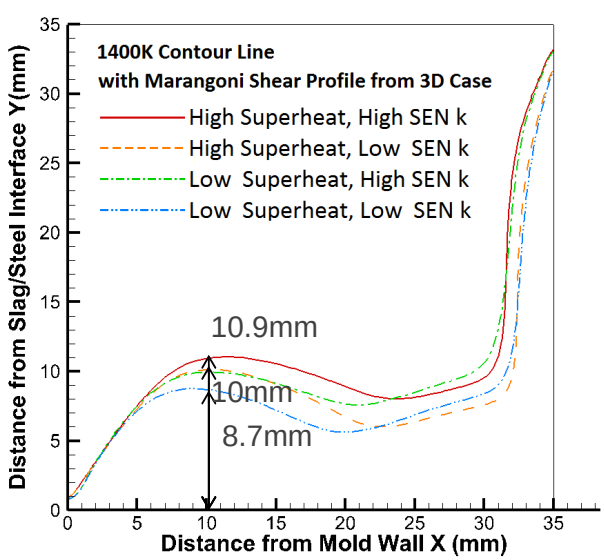


Low SEN conductivity

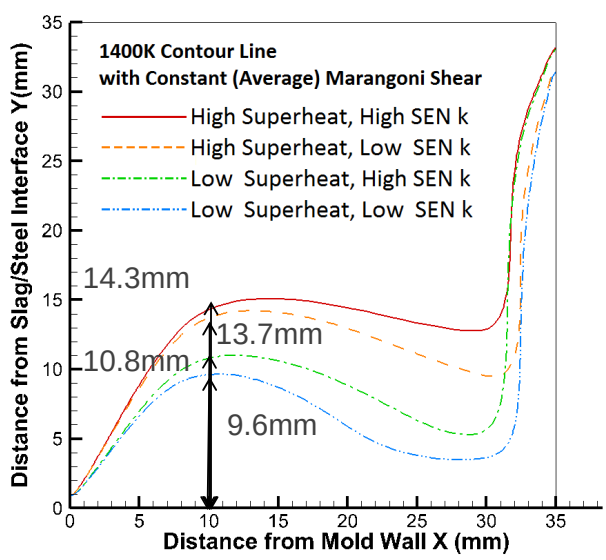


High SEN conductivity

Effects of Initial Superheat & SEN k on Liquid Slag Layer Thickness

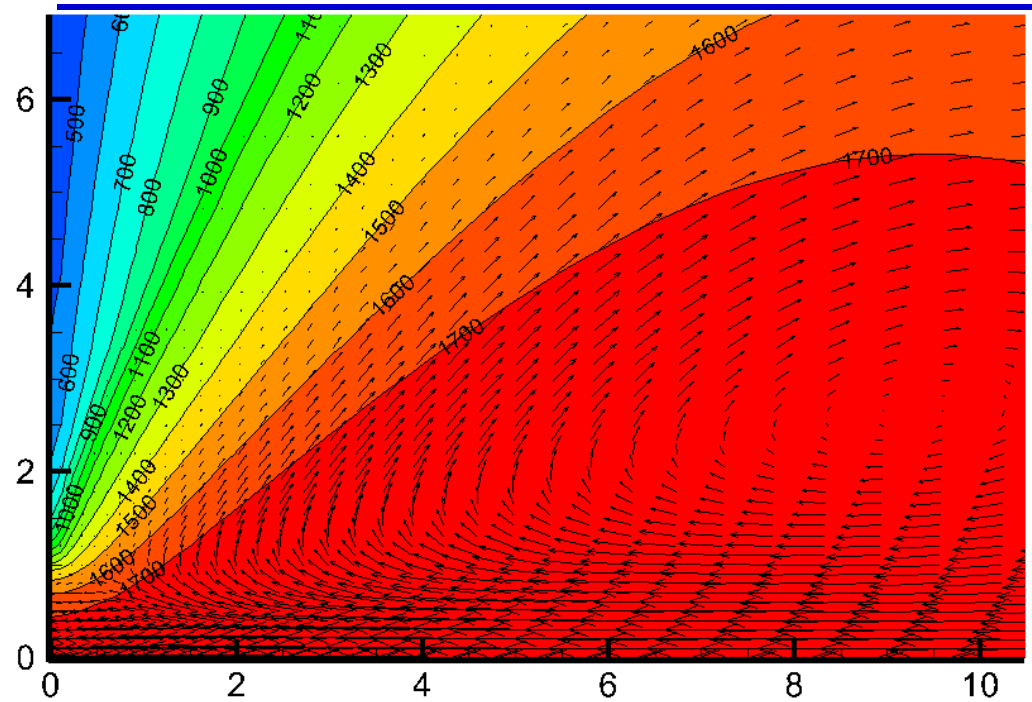


Using Marangoni shear profile from 3D simulation



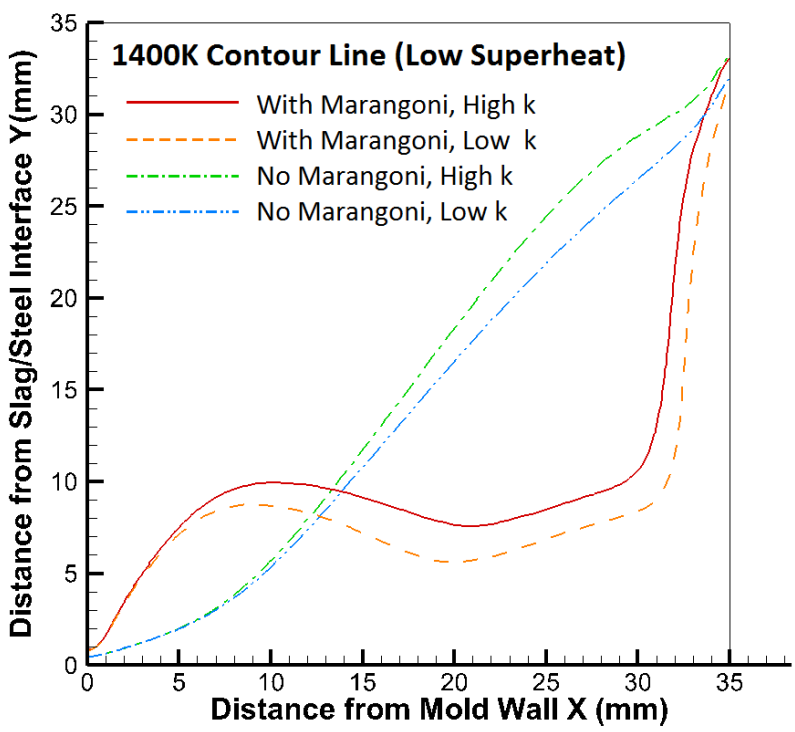
Using Average Marangoni shear

Recirculation Caused by Marangoni Shear



Flow along slag/steel interface accelerates towards meniscus by Marangoni shear, then rises and recirculates

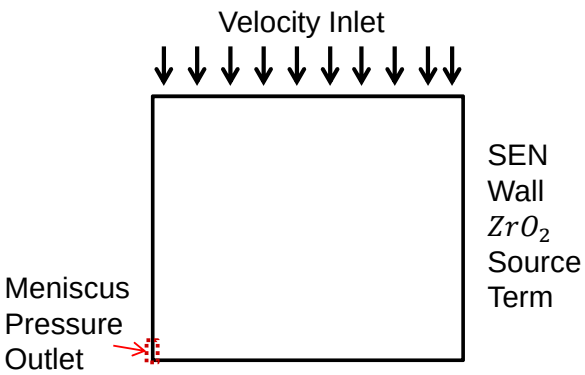
Effects of Marangoni Shear on Liquid Slag Layer Thickness



The presence of Marangoni shear increases liquid slag layer thickness at meniscus.

Without Marangoni shear, liquid slag layer thickness changes little with SEN conductivity at meniscus.

2D ZrO_2 Diffusion Model

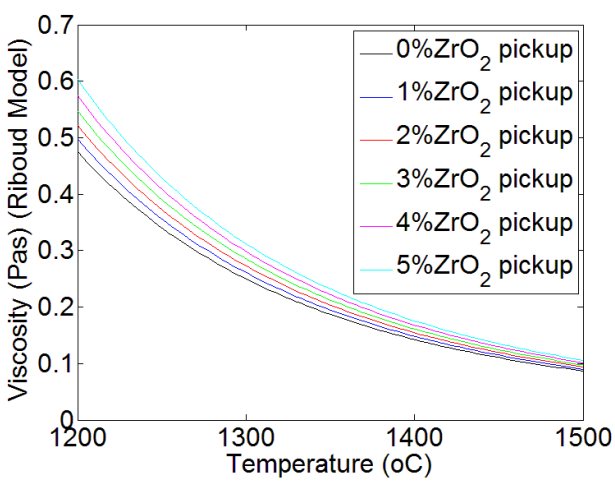


- Same 2D mesh and flow/heat conditions
- ZrO_2 source term at he SEN wall
- Compare ZrO_2 concentration at meniscus, and see the effect on viscosity

$$\text{Source Term} = \text{erosion rate} \times density \times ZrO_2\%$$

SEN Material	ZG806H	ZG797H
ZrO_2 Source Term (g/m^2s)	0.366	0.665

Viscosity Calculation & Riboud Model



Linear Fit: $\ln(A) = -0.324\emptyset - 19.177$

$B = 7546\emptyset + 16404$

Correction Coefficient:

$$\alpha = \frac{A(\emptyset)Te^{\frac{B(\emptyset)}{T}}}{A(0)Te^{\frac{B(0)}{T}}} = e^{-0.324\emptyset + \frac{7546\emptyset}{T}}$$

- Riboud Model:
- $\eta(Pas) = AT(K)e^{B/T(K)}$

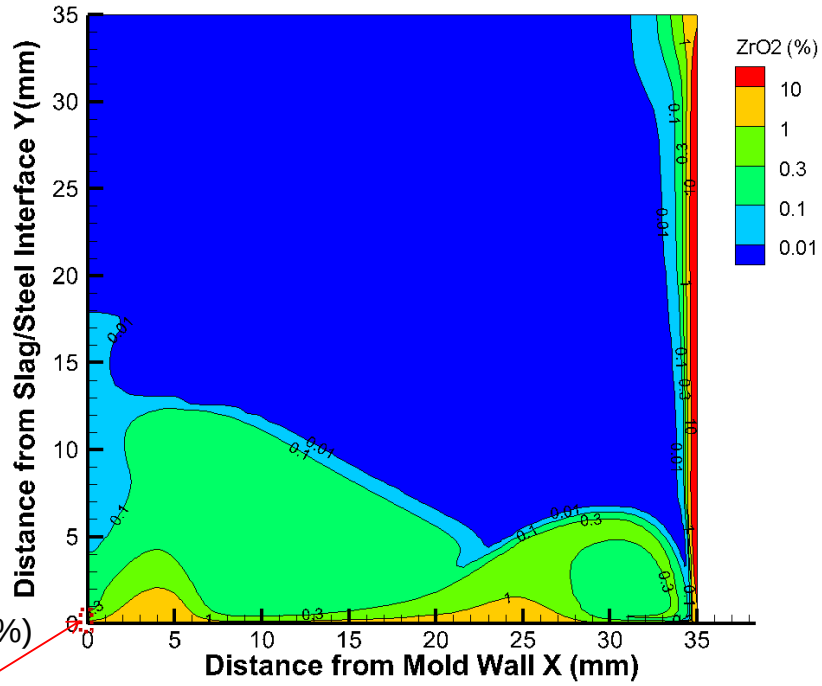
$$A = \exp(-19.81 + 1.73X_{"CaO"} + 5.82X_{CaF2} + 7.02X_{"Na2O"} - 35.76X_{"Al2O3"})$$

$$B = 31140 - 23896X_{"CaO"} - 46356X_{CaF2} - 39159X_{"Na2O"} + 6883X_{"Al2O3"})$$

- $X_{"SiO2"} = X_{SiO2} + X_{P2O5} + X_{TiO2} + X_{ZrO2}$
- $X_{"CaO"} = X_{CaO} + X_{MgO} + X_{Fe2O3} + X_{MnO2}$
- $X_{"Al2O3"} = X_{Al2O3} + X_{B2O3}$
- X_{CaF2}
- $X_{"Na2O"} = X_{Na2O} + X_{K2O} + X_{Li2O}$

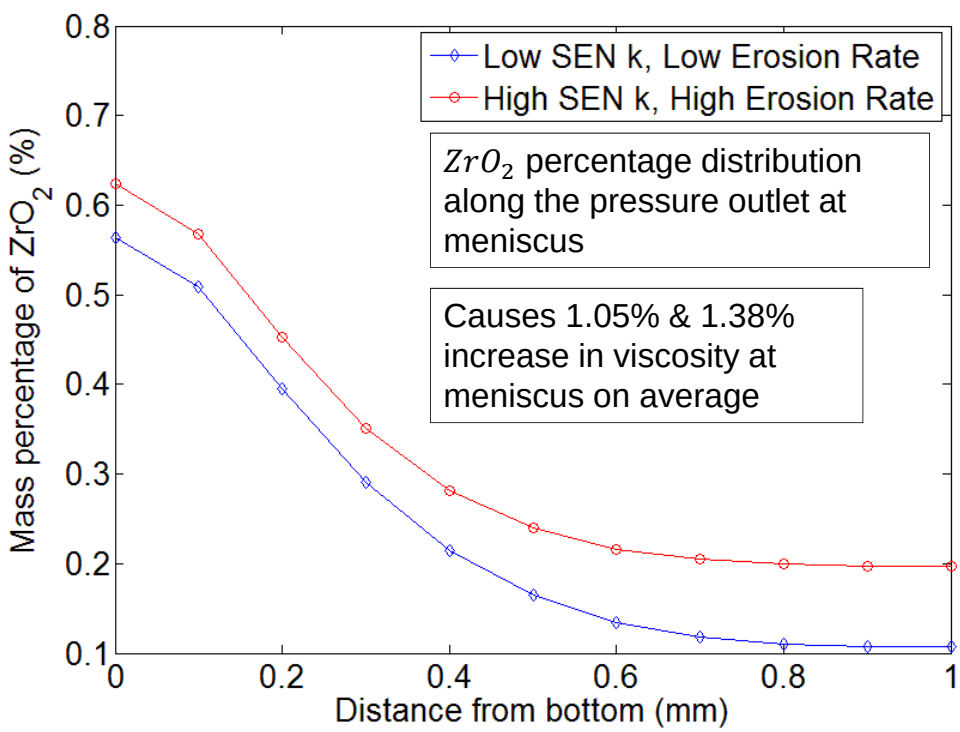
P. V. Riboud, Y. Roux, L. D. Lucas and H. Gaye: Fachber. Huttenprax. Metallweiterverarb, 1981, vol.19, pp. 859-69.

ZrO_2 Concentration



ZrO_2 concentration (%) at meniscus
See next slide

ZrO_2 Concentration & Viscosity Change at the meniscus outlet



ZrO_2 percentage distribution along the pressure outlet at meniscus

Causes 1.05% & 1.38% increase in viscosity at meniscus on average

Conclusions-Modeling

- Several computational models have been developed to investigate refractory effects on heat transfer, fluid flow, and erosion product diffusion in meniscus region near SEN
- When initial superheat doubles from 24K to 49K, top surface superheat increases by around 10K (from -2K to 8K in the SEN-Wide face region). Heat flux increases slightly by 2.5kW/m^2
- Near SEN & wide face meniscus, Marangoni shear effect is ~10 times of the ordinary shear produced by steel movement; but in middle of mold, this effect is negligible (less than 1%) .
- Higher Initial superheat generates more Marangoni shear near meniscus, results in thicker liquid slag layer.
  (Around 4mm increase for the average Marangoni case)
- Higher SEN conductivity bring more heat to slag near wide face meniscus, results in thicker liquid slag layer.

  (Around 1mm increase for the average Marangoni case)

Conclusions-Mechanism

- Likely Mechanism to explain SEN conductivity effect:
  - Hotter SEN wall creates larger temperature gradient in thin SEN/WF gap, increasing effect of Marangoni flow towards meniscus.
  - Increased flow and convection mixing in slag layer makes it thicker.
  - Thicker slag layer leads to better slag infiltration into meniscus gap, more uniform heat transfer, and less longitudinal facial cracks.

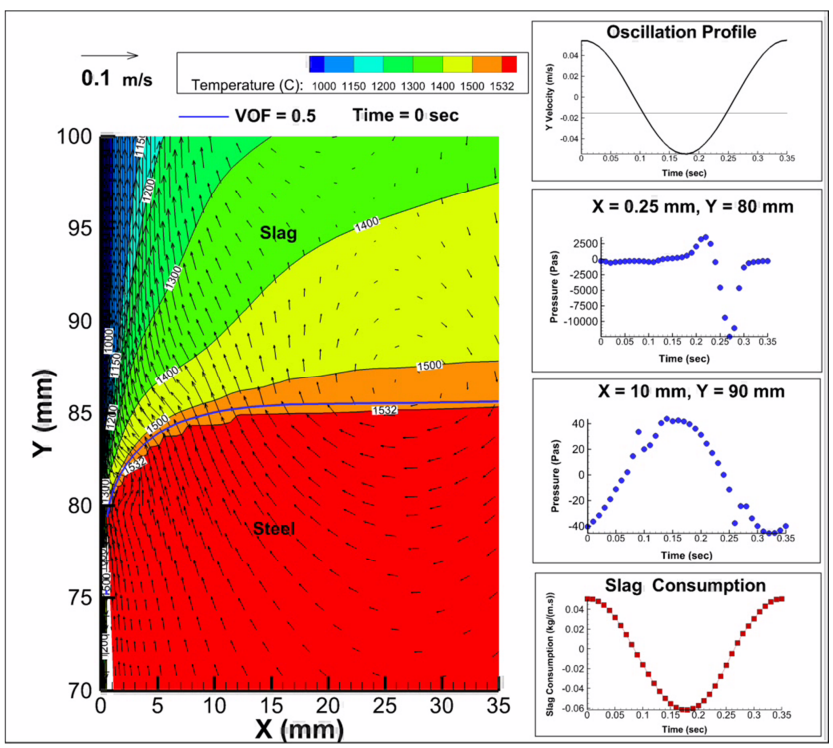
- SEN conductivity has little effect on molten steel temperature near wide face meniscus.

- SEN erosion rate has little effect on viscosity near meniscus. Thus, likely not an important mechanism for LFC

Future Work

- Develop a Meniscus region Transient Thermal-flow model based on previous CCC work.
- Add slag layer to the 3D steel model to fully couple the shear and heat transfer at slag/steel interface.
- Investigate the effects of other process condition like mold width, submergence depth, nozzle outlet angle.

Meniscus region Transient Thermal-flow model (Previous)



Acknowledgments

- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Magnesita Refractories, Nippon Steel and Sumitomo Metal Corp., Nucor Steel, Postech/ Posco, Severstal, SSAB, Tata Steel, ANSYS/ Fluent)
- Magnesita for providing SEN refractory material data
- Hyunjin Yang for providing the 3D FLUENT mesh and steel flow results.