ANNUAL REPORT 2012

UIUC, August 16, 2012

Mold Heat Transfer Using CON1D and Slag Consumption Model

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Objectives

- Develop an accurate predictive model of mold slag consumption for slab casting, including the effects of mold oscillation parameters, slag properties.
- Improve CON1D to better simulate heat transfer in the interfacial gap (in addition to mold and shell)
- Apply model(s) to simulate the mold region heat transfer in real commercial casters, and validate with plant data.

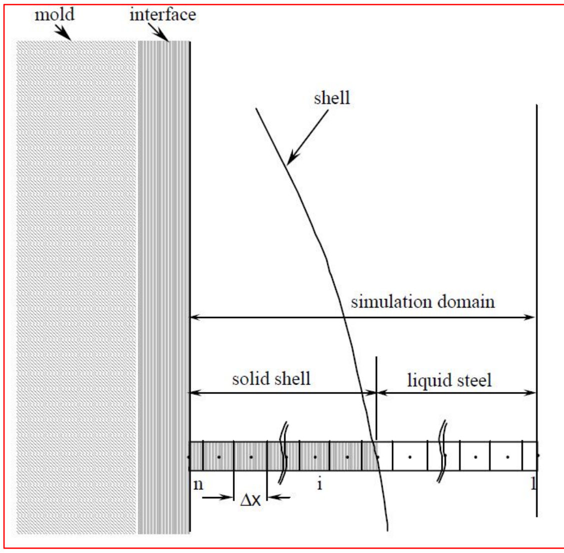
Tools

- CON1D (macroscopic heat transfer in mold, interface and shell)
  - Current: Wide face shell (input slag consumption and ferrostatic pressure controls gap thickness profile)
  - Future enhancement: Corner region (steel shrinkage and mold distortion control gap thickness profile)
- FLUENT meniscus model (meniscus heat transfer, fluid flow, meniscus shape, slag consumption)
- Plant measurements (oscillation mark shape, hook, mold heat transfer, cooling water temp. rise)

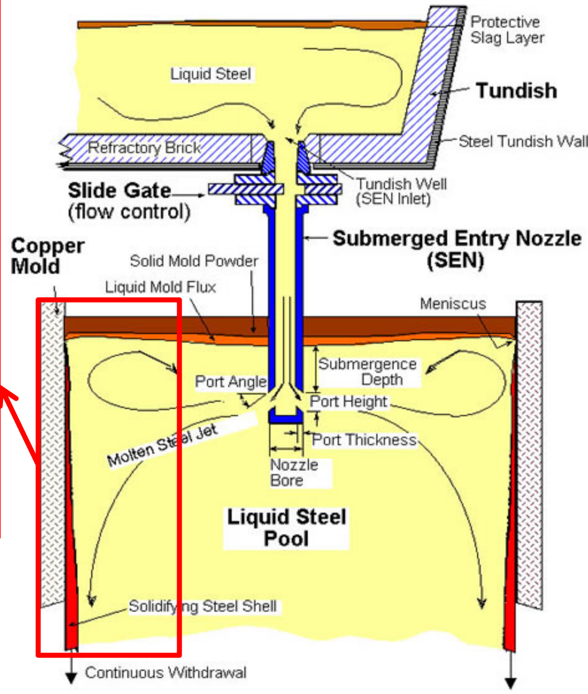
CON1D Model

Model Prediction	Validation
• Heat flux variation • Mold Temperature	thermocouples embedded in mold wall
• Cooling water temperature increase	water temperature measurement
• Shell thickness	breakout shell or tracer element
• Slag layer thickness	slag film samples taken from mold wall
• Shell temperature	optical pyrometers, thermocouples in the strand
• Ideal taper	
• Mold friction and lubrication state	friction signal
• slag state	crystalline vs. glassy
• slag shear/fracture	transient temperature variation

CON1D: Shell Region

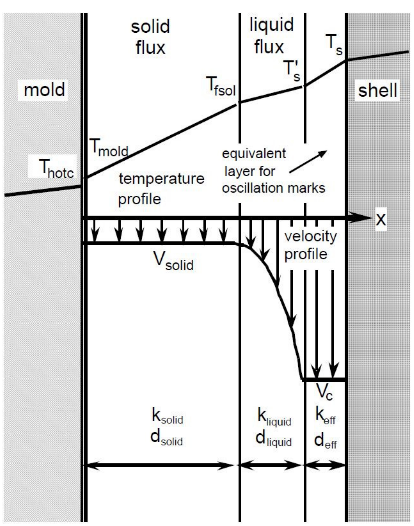


$$\rho_{steel} Cp^{*}_{steel} \frac{\partial T}{\partial t} = k_{steel} \frac{\partial^2 T}{\partial x^2} + \frac{\partial k_{steel}}{\partial T} \left(\frac{\partial T}{\partial x} \right)^2$$

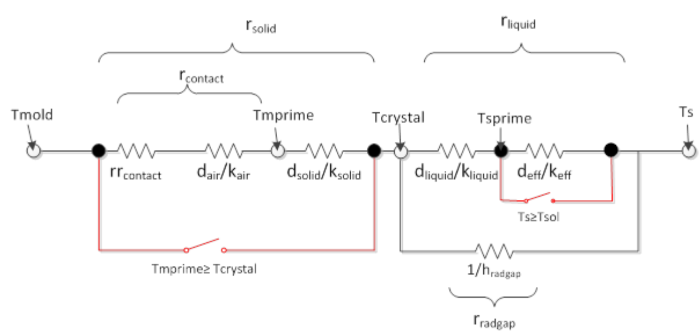


CON1D Manual V10.10.01

CON1D: Interface Region



Resistances to Heat Transfer in interface:



Simplified Form of Navier-Stokes Equation:

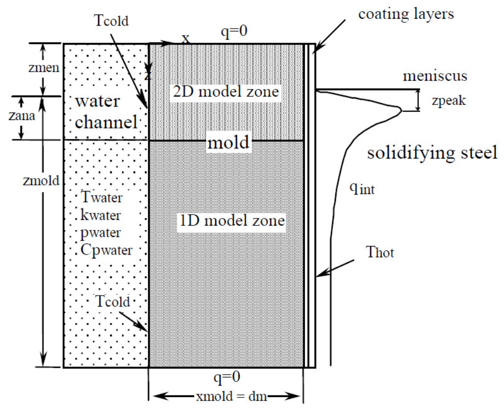
$$\frac{\partial}{\partial x}\left(\mu \frac{\partial V_z}{\partial x} \right) = (\rho_{steel} - \rho_{slag}) g$$

Mass Balance:

$$\frac{Q_f \times V_c}{\rho_{flux}} = V_{solid} d_{solid} + \bar{V}_{liquid} d_{liquid} + V_c d_{osc}$$

CON1D Manual V10.10.01

CON1D: Mold Region



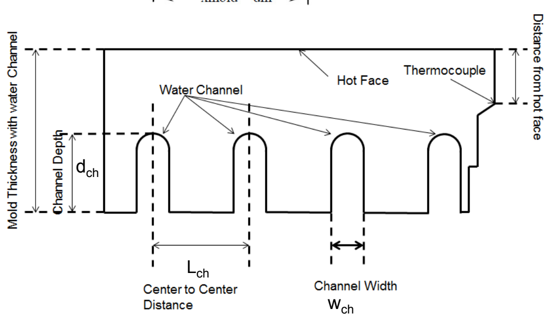
Analytical Solution of Laplace equation 2D region:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial z^2}=0$$

1D Region:

$$T_{hotc}=T_{water}+q_{\text{int}}\left(\frac{1}{h_{water}}+\frac{d_m}{k_m}\right)$$

Heat Transfer Coefficient between cold face and cooling water



$$h_{fin}=\frac{h_w w_{ch}}{L_{ch}}+\frac{\sqrt{2h_w k_{mold}\left(L_{ch}-w_{ch}\right)}}{L_{ch}}\tanh\sqrt{\frac{2h_w d_{ch}^2}{k_{mold}\left(L_{ch}-w_{ch}\right)}}$$

$$h_w=\frac{k_{water}}{D}\left(5+0.015\,\text{Re}_{waterf}^{c_1}\,\text{Pr}_{waterw}^{c_2}\right)$$

CON1D Manual V10.10.01

Example CON1D Application

Input based on geometry

- Water channel dimension
- Mold thickness dimensions
- Coating layers in mold hot face

Inputs based on casting condition

- Casting speed
- Pouring temperature
- Meniscus location
- Liquid pool depth
- Nozzle location
- Slab Dimensions
- Composition of Steel and Slags
- Cooling water velocity

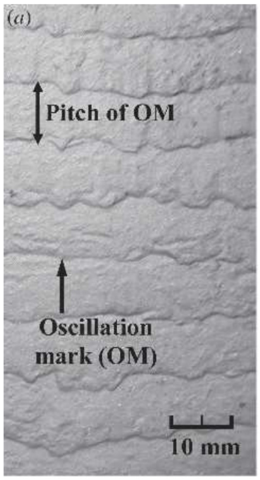
Inputs based on extra measurements

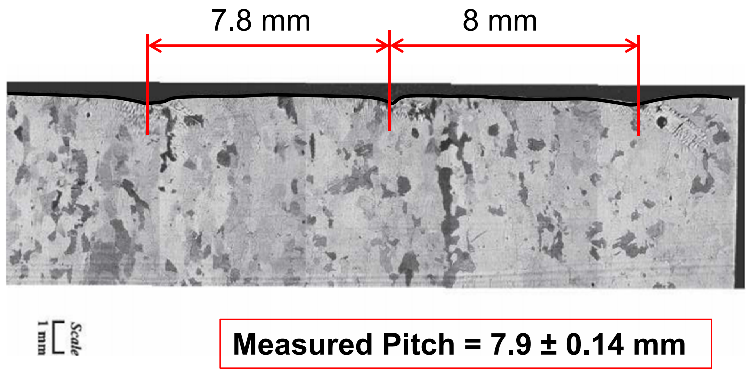
- Mold Oscillation
  - Stroke
  - Frequency
- Oscillation Mark Dimensions
  - Width
  - Depth
- Slag consumption

Tuning/Adjustment parameters
(to match mold heat flux & TC temps)

- Solid Slag velocity ratio
- Friction coefficients (static/moving)
- Air gap between Hot face and Solid slag
- Water channel Scale?

Oscillation Mark : Pitch





Measured Pitch = 7.9 ± 0.14 mm

- **Theoretical Pitch**

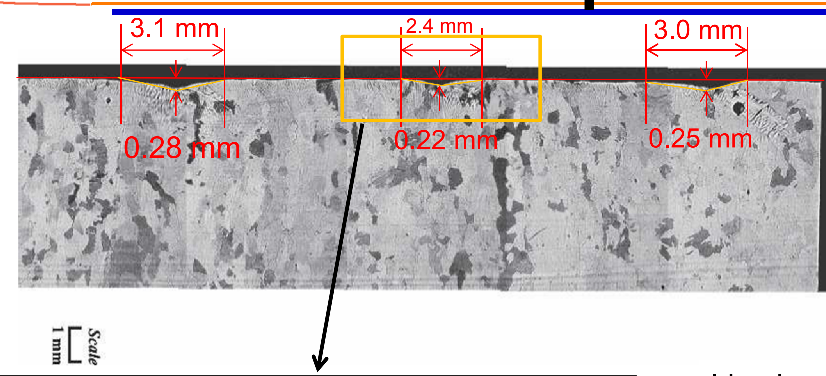
  Equation for theoretical pitch = $\frac{v_s}{f}$

Casting Speed (v_s)	23.23 mm/sec
Oscillation Frequency (f)	2.9 Hz

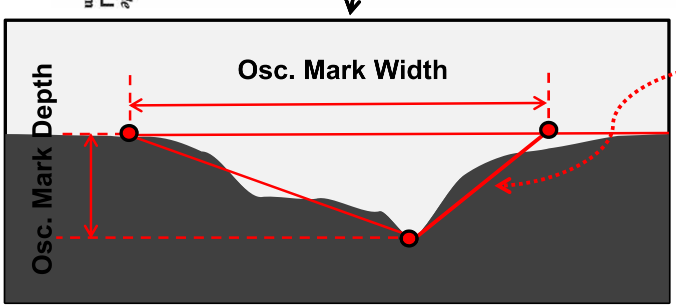
Theoretical Pitch = 8 mm

Sengupta, J., B. G. Thomas, H. J. Shin, G. G. Lee, and S. H. Kim, Metallurgical and Materials Transactions A, 37A:5, May 2006

Oscillation Mark: Width and Depth



Sengupta, J., B. G. Thomas, H. J. Shin, G. G. Lee, and S. H. Kim, Metallurgical and Materials Transactions A, 37A:5, May 2006



Line is averaged through edge of OM such that the area is averaged

Measured Oscillation Mark,
Width = 2.83 ± 0.38 mm
Depth = 0.25 ± 0.03 mm

Oscillation Mark Samples: Depth Prediction

- According to SHIN[1], Oscillation Mark Depth at POSCO is estimated by:

$$(D_{OM})_{predicted} = 0.4511 \times \mu_{1300°C}^{\ 0.6515} \times t_n^{\ 0.1391} \times Vc^{-1.208} \times Superheat^{-0.09126}$$

$\mu_{1300°C}$ = Viscosity at 1300°C
V_c = Casting speed
t_n = Negative strip time
Superheat = $T_{tundish}$ - $T_{liquidus}$

Here, $T_{liquidus}$ can be calculated using[2]

$$\begin{aligned} T_{liquidus} = Tpure - \{&78[\%C] + 7.6[\%Si] + 4.9[\%Mn] + 34.4[\%P] + 38[\%S] \\ &+ 1.04[\%\ Cr] + 4.69[\%\ Ni] + 5.32[\%\ Cu] + 2.6[\%\ Mo] + 10.24[\%\ Ti] \\ &+ 12.95[\%\ V] + 10.24[\%\ Nb] + 0.24[\%\ W] + 60[\%\ N]\} \end{aligned}$$

T_{pure} = Melting point of pure iron (1536°C)
%i = Initial liquid concentration of element i

[1] Ho-Jung SHIN and Brian G. THOMAS, Continuous Casting Consortium Annual Meeting 2005.
[2] Won, Y-M. and B. G. Thomas, Metallurgical and Materials Transactions A, 32A:7, 1755-1767, 2001

Oscillation Mark: Depth Prediction

Steel Composition:

C	Si	Mn	P	S
0.003%	0.08%	0.08%	0.013%	0.009%

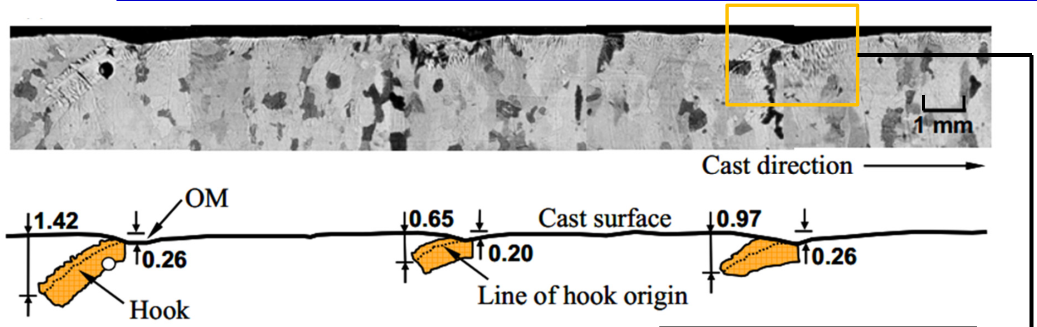
$$\boldsymbol{T_{liqidus} = 1533.9°C}$$

$\mu_{1300°C}$	Viscosity of slag at 1300°C	2.62 Poise
t_n	Negative time strip	0.12 sec
V_c	Casting Speed	1.4 m/min
Superheat	$T_{tundish} - T_{liquidus}$	1568 – 1533.9 = 34.1°C

$$\boxed{\boldsymbol{(D_{OM})\ predicted = 0.31\ mm}}$$

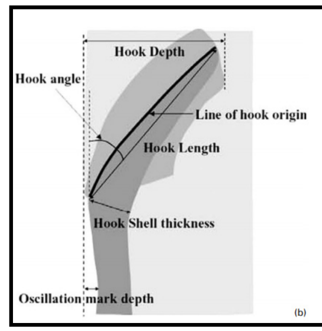
Measured OM depth = **0.25 ± 0.03 mm**, almost matches

Oscillation Mark : Hook Depth



Sengupta, J., B. G. Thomas, H. J. Shin, and S. H. Kim, AISTech 2006 Steelmaking Conference Proc

Measured Hook Depth = 1.01 ± 0.39 mm



G.-G. Lee et al, Ironmaking and Steelmaking 2009, VOL 36

Oscillation Mark: Hook Depth Prediction

- According to Lee[1]–

  Predicted Hook Depth

$$= 10^{-31.0874} \times V_c^{-0.61416} \times F^{-0.46481} \times T_s^{-0.18782} \times L_f^{0.041863} \times T_{sol}^{10.692}$$

V_c	Casting Speed (m/min)	1.4 m/min
F	Oscillation Frequency (cycle/min)	2.9 × 60 cycle/min
T_s	Superheat Temperature = $T_{tundish} - T_{liquidus}$ (°C)	1568 – 1533.9 =34.1°C
L_f	Mean level fluctuation during sampling (mm)	2 mm
T_{sol}	Solidification temperature of Slag (°C)	1101°C

Predicted Hook Depth = 1.07 mm

[1] Lee, G.G, H.-J. Shin, S.-H. Kim, S.-K. Kim, W.-Y. Choi, and B.G. Thomas, Ironmaking and Steelmaking, 36: 1, 39 49, 2009

Oscillation Mark Consumption: CON1D Model

- Oscillation marks filled with slag and moving at the casting speed consume slag at the following rate –

$$Q_{OM} = \frac{0.5 \times \rho_{slag} \times d_{mark} \times w_{mark}}{L_{pitch}}$$

ρ_{slag}	Density of Slag (kg/m^3)	2660 kg/m^3
d_{mark}	Depth of OM (m)	0.25 mm
w_{mark}	Width of OM (m)	2.83 mm
L_{pitch}	Pitch length (m)	8.0 mm

$$\boxed{Q_{OM} = 0.12\ \mathrm{kg/m^2}}$$

Total Slag Consumption

The total slag consumption (Q_{slag}) can be divided into three components –

$$Q_{slag} = Q_{sol} + Q_{liq} + Q_{OM}$$

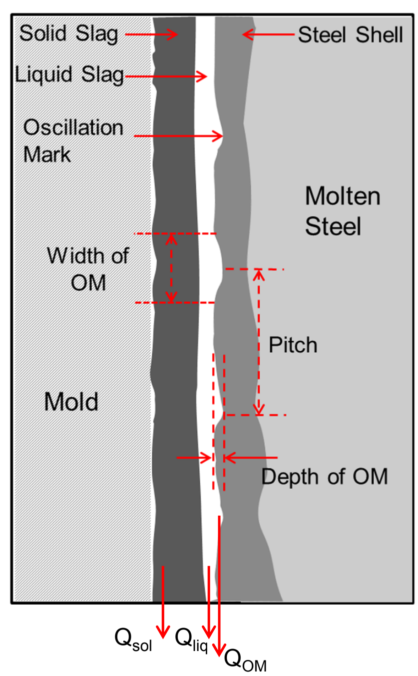
Here,

Q_{sol} = The solid part of the slag that sticks to the mold wall after resolidifing from liquid slag.

Q_{liq} = Layer of thin continuous liquid slag.

Q_{OM} = Slag carried away by the Oscillation Marks.

$$\frac{Q_{slag} \times V_c}{\rho_{slag}} = V_{solid} d_{solid} + \bar{V}_{liquid} d_{liquid} + V_c d_{osc}$$



Total Slag Consumption: SHIN's[1] Equations

$$Q_{slag} = (\underbrace{2.5\times10^{-2}\times\rho_{slag}\times k^{1.43}\times(\sqrt{\frac{2\cdot\Delta\gamma}{\Delta\rho\cdot g}})^{0.566}\times t_n^{0.389}\times V_c^{-1.49}}_{q_{OM}\,(gm^{-1}cycle^{-1})} + \underbrace{0.507\times e^{3.59\times tp}}_{q_{lub}\,(gm^{-1}cycle^{-1}) = q_{solid}+q_{liuid}})\times\frac{f}{V_c}$$

ρ_{slag}	Density of slag (kg/m^3)	2660 kg/m^3
k	Empirical Constant – depends on properties of slag (found using Shin's paper)	14
$\Delta\gamma$	Surface Tension of Steel – Surface Tension of Slag (N/m)	1.7 – 0.419 = 1.281 N/m
$\Delta\rho$	Density of Steel – Density of Slag (kg/m^3)	7000-2660 =4340 kg/m^3
t_n	Negative time Strip (sec)	0.12 sec
V_c	Casting Speed (mm/s)	23.23 mm/s
f	Frequency of Oscillation (Hz or cps)	2.9 Hz
g	Gravitational Acceleration (ms^{-2})	9.81 ms^{-2}

q_{OM}= 0.75 $gm^{-1}cycle^{-1}$ → Q_{OM} = 0.09 kg/m^2

$Q_{slag} = 0.23\ kg/m2$

[1] 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.

Input Variables for CON1D Simulation

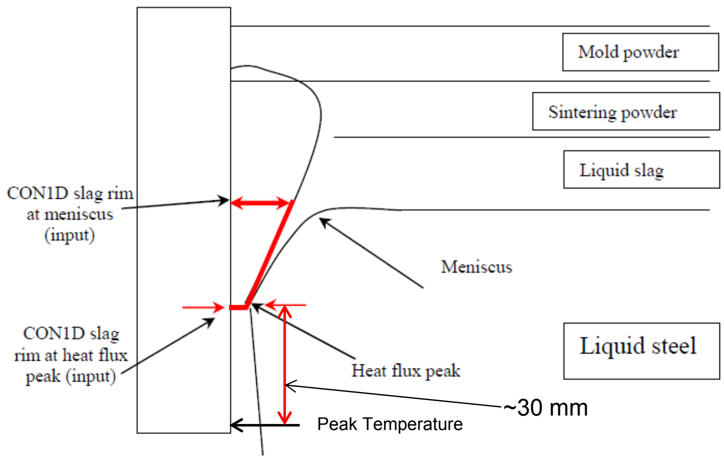
- Steel Solidus and Liquidus Temperature:
  - Composition of steel:

Using Clyne-Kurz Simple Analysis Segregation Model,

Solidus Temperature: 1517.89 °C
Liquidus Temperature: 1533.9 °C

- Mold Thermal Conductivity:
  - 375 W/(mK) is a max value for Cu-P or Cu-Ag molds
  - 350 W/(m.K) is a typical value for Cu-Cr-Zr molds
  - Some molds were found to have as low as 315 W/(m.K)
  - Better to have plant measurements
- Flux Conductivity:
  - 1~1.5 W/(m.K) general values for solid / liquid conductivity
  - Values are provided by suppliers

Slag Rim Dimensions



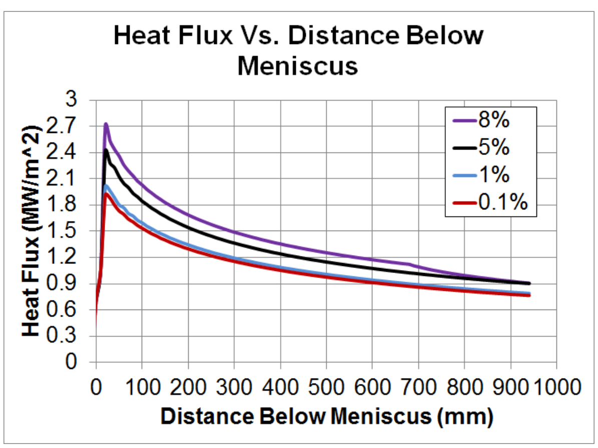
CON1D Manual V 10.10.01

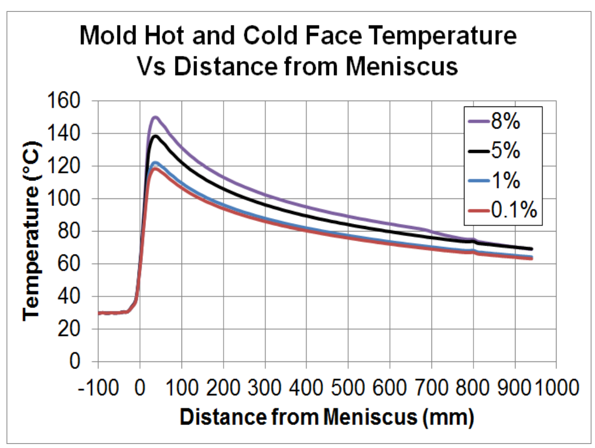
- Level fluctuations and meniscus shape cause larger slag rim, which causes location of heat flux peak to lower below meniscus
- Heat flux peak is not same as temperature peak.
- Peak heat flux is typically around ~30 mm above the maximum mold temperature [1]

[1] E. Takeuchi and J.K. Brimacombe, Matallurgical Transactions B, Vol 15B

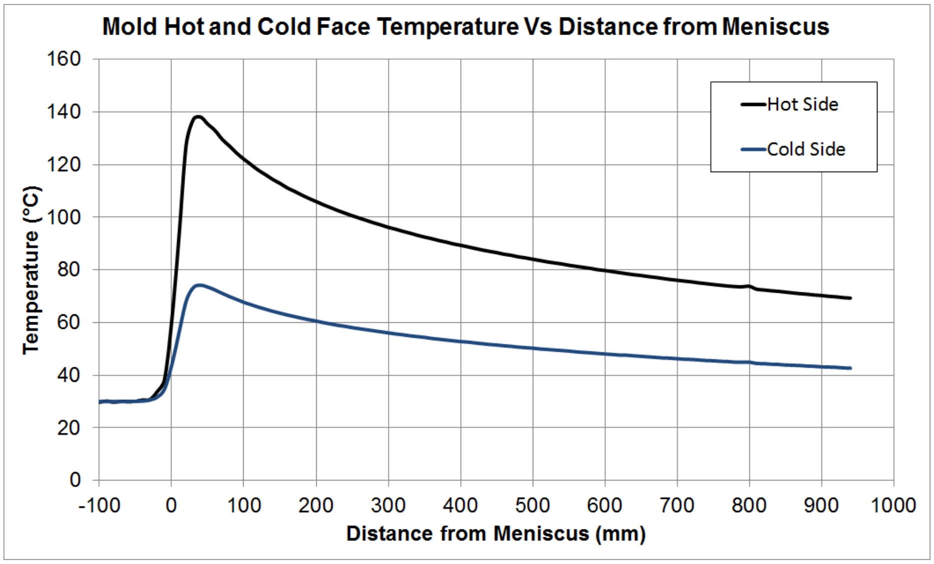
Solid Flux Velocity Ratio (parametric study)

- Ratio of average solid flux velocity to casting speed
  - Can be a function of distance below meniscus or can be constant
  - Can be adjusted to match heat flux, thermocouple predictions etc.



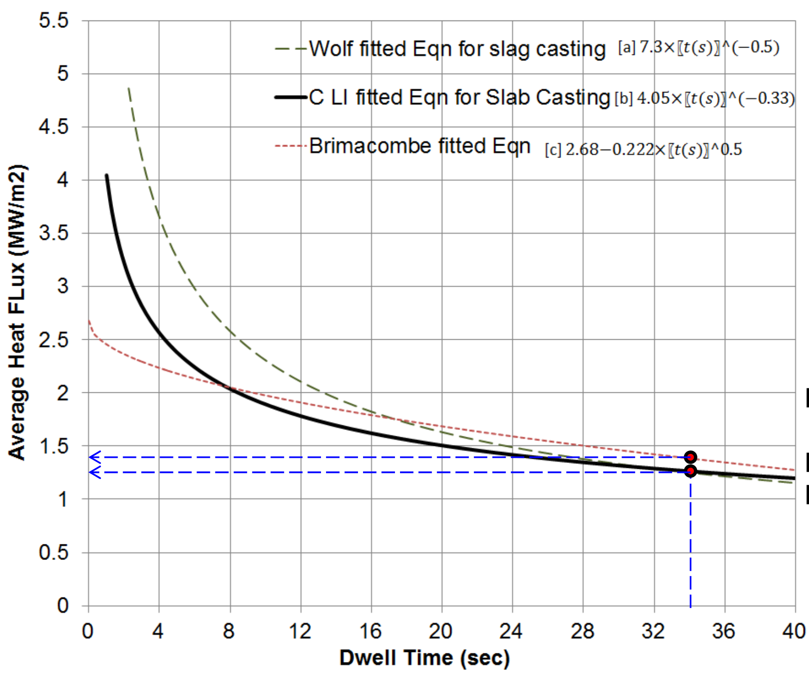


Results for Sample Case: Hot and Cold Face Temperature



- At 40mm from meniscus Hot side and cold side reaches maximum value of ~138°C and ~74°C respectively

Heat Flux From Dwell time



[a] Brimacombe, J.K.Canadian Metallurgical Quarterly, 15 (2)

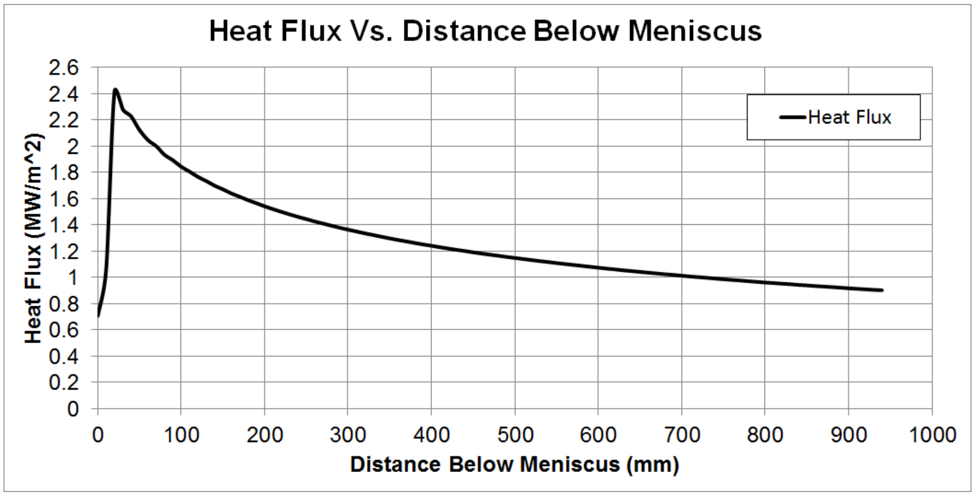
[b] Li, C. and Thomas, B. G, The Brimacombe Memorial Symposium, Vancouver, Canada, Oct. 1-4, 2000

[c] Wolf M.M., Iron & Steelmaker, V. 23, Feb., 1996, p47

Based on **34s** sec dwell time,

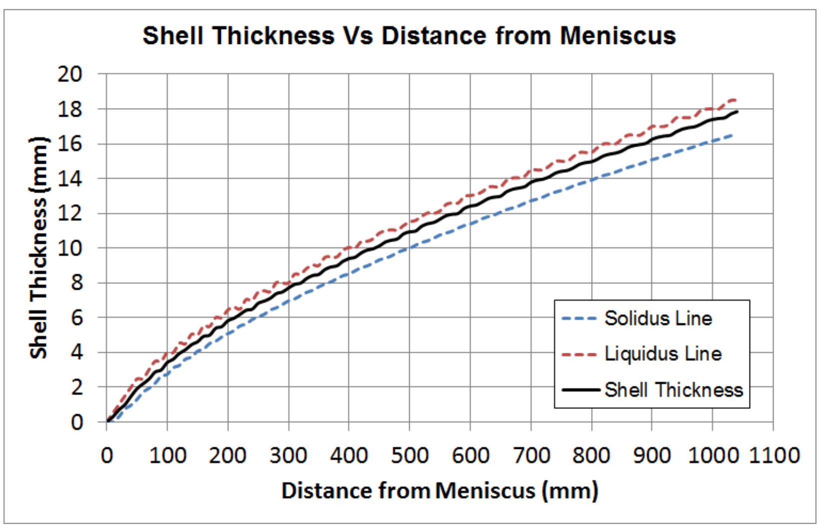
Brimacombe's Eqn ~**1.4 MW/m²**
Li's Eqn ~**1.3 MW/m²**

Heat Flux



- Mean heat flux from CON1D is 1. 3 MW/m^2 which is close to the value obtained by using Li C[b] and Brimacombe's equations[a] for slab casting for 34 sec dwell time (1.3 MW/m^2 and 1.4 MW/m^2 respectively).
- Heat flux at mold exit is 0.9 MW/m^2 given by CON1D while Li C and Brimacombe's Equation gives 0.8 and 0.7 MW/m^2

Shell Thickness

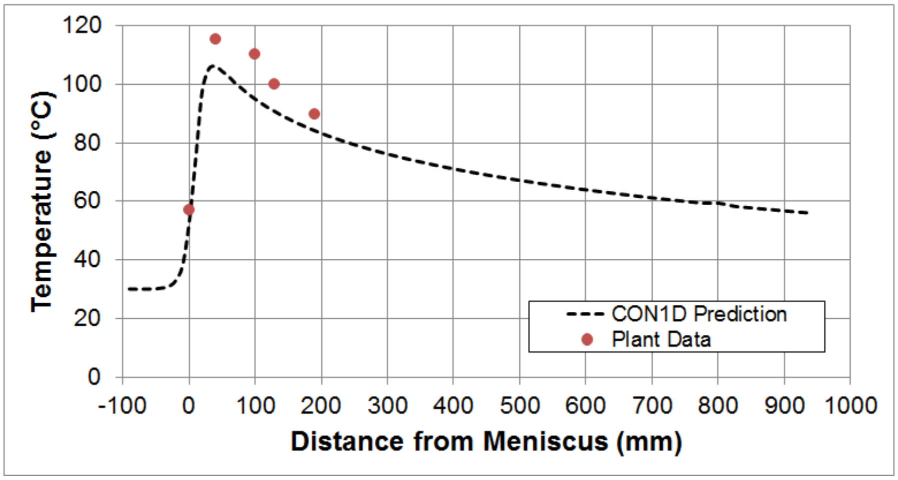


Shell thickness curve with fraction solid for shell thickness location 0.3

- Shell thickness predicted by CON1D at exit ~18 mm

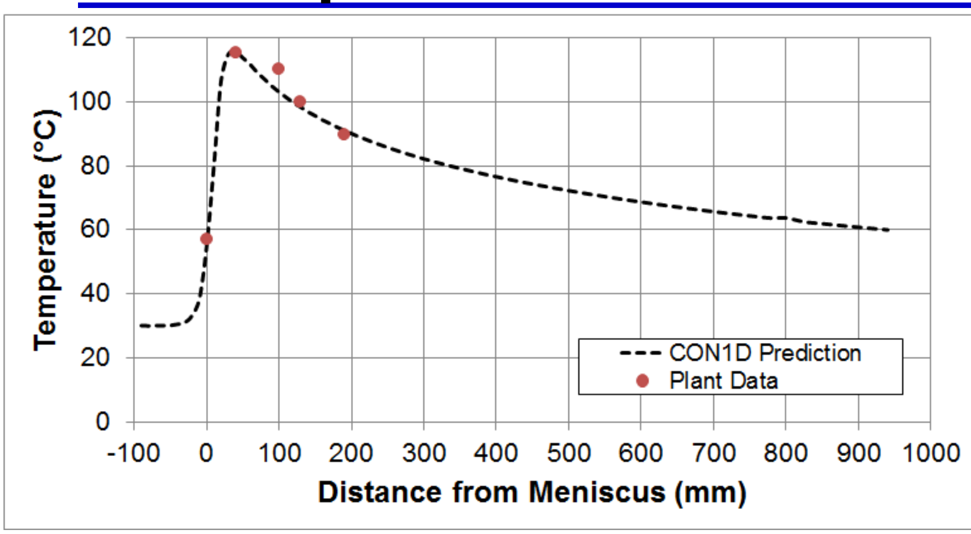
Thermocouple Temperature Prediction

- Thermocouples were located at **5 mm** from the hot face.



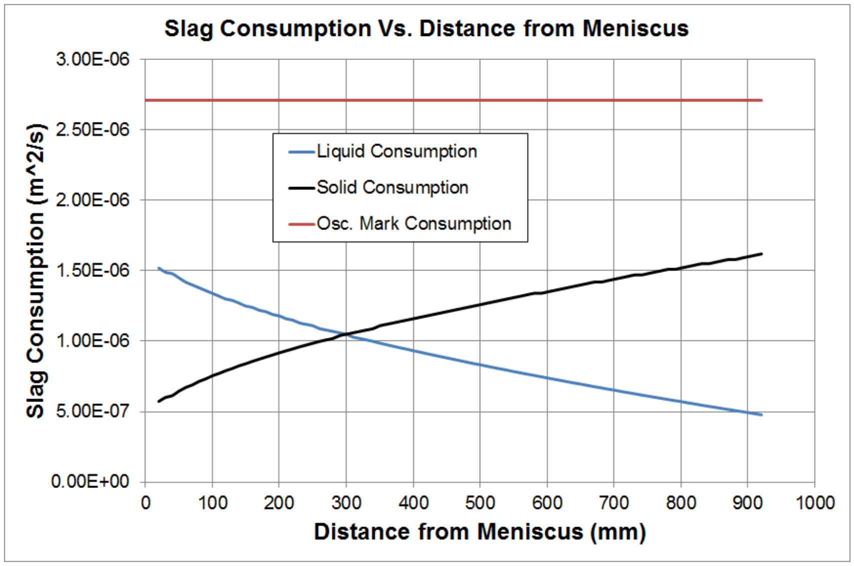
- CON1D predicts lower values at the thermocouples.
- This can be explained by two phenomena-
  - Contact Resistance at Thermocouple contact point
  - 1D heat transfer model in CON1D gives smaller value.

Corrected Thermocouple Temperature Prediction



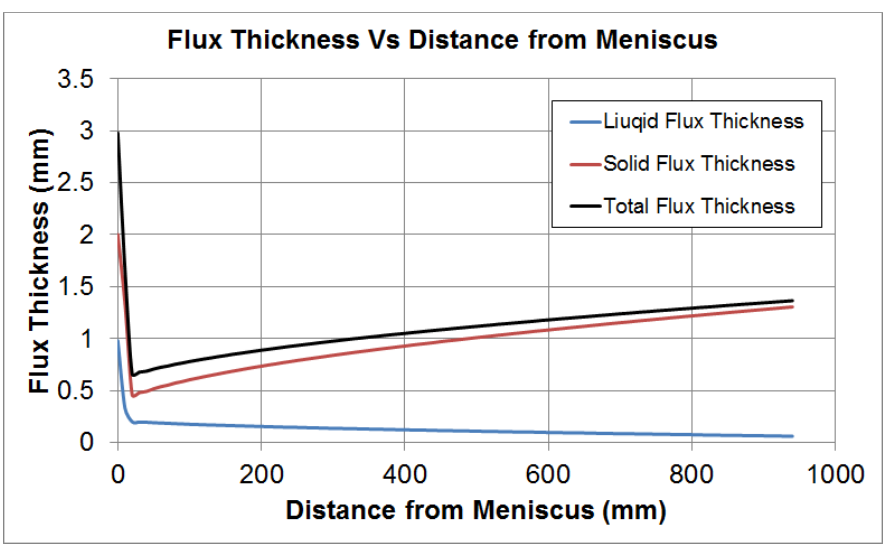
- Thermo couple temperature correction offset was take 1.5 mm for this case calculated using the new script that gives 3D accuracy for geometry in CON1D
- Thermocouple temperature prediction by CON1D with offset closely matches the data from NSC plant.

Flux Consumption



- Total consumption matches with the plant data
- Liquid flux consumption decreases while solid flux consumption increases down the mold
- Oscillation mark consumption stays constant because average model is used for osc. Consumption

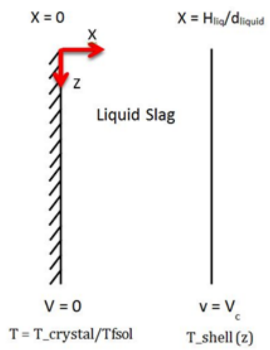
Flux Thickness



- Solid flux thickness at exit = 1.3 mm
- Liquid flux thickness at exit = 0.06 mm
- Total flux thickness at exit = 1.36 mm

Corner Model

- Current model works best near the center.
- Ferrostatic pressure assumed to directly exert force on the liquid slag layer
- In the corner, gap size defines the slag layer thickness (not pressure from steel)
- Liu and Alonso[1]came up with model that can predict the pressure and consumption based on given slag layer thickness.



Equations to Solve:

$$\frac{d}{dx}\left(\mu\frac{dV_z}{dx}\right)=\frac{dP}{dz}-\rho g$$

$$\frac{\partial^2 T}{\partial x^2}=0$$

Velocity :

$$V_z = V_{casting}\frac{x^{n+1}}{H_{liq}^{n+1}}+\left(\frac{C}{\mu_0 H_{liq}^{n+3}\left(T_0-T_{fsol}\right)^n}+\frac{V_{casting}(n+2)(n+3)}{H_{liq}^{n+2}}\right)\frac{x^{n+2}-x^{n+1}H_{liq}}{n+2}$$

Consumption:

$$Q=\rho W\int_0^{H_{liq}} V_z dx$$

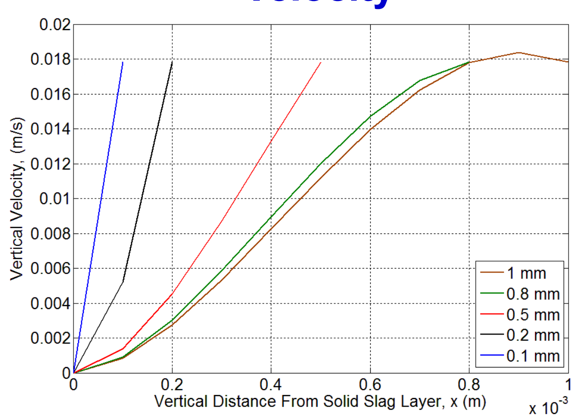
$$p(z)=\underbrace{C\int_{z=0}^{z}\frac{1}{H_{liq}^3\left(T_{shell}-T_{fsol}\right)^n}dz}_{\mathrm{I1}}+\underbrace{\int_{z=0}^{z}\frac{V_{casting}\mu_0(n+2)(n+3)\left(T_0-T_{fsol}\right)^n}{H_{liq}^2\left(T_{shell}-T_{fsol}\right)^n}dz}_{\mathrm{I2}}+\underbrace{\int_{z=0}^{z}\rho g dz}_{\mathrm{I3}}+C_1$$

Where C and C1 depends on the Boundary Conditions. In this case two boundary conditions are applied.

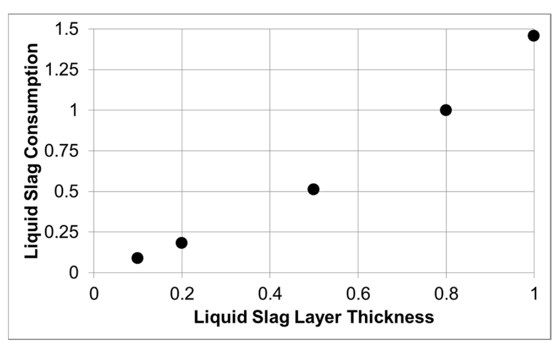
[1] Liu, Rui, Alonso Mathew, ME 550 Project

Corner Model – Preliminary results

Velocity

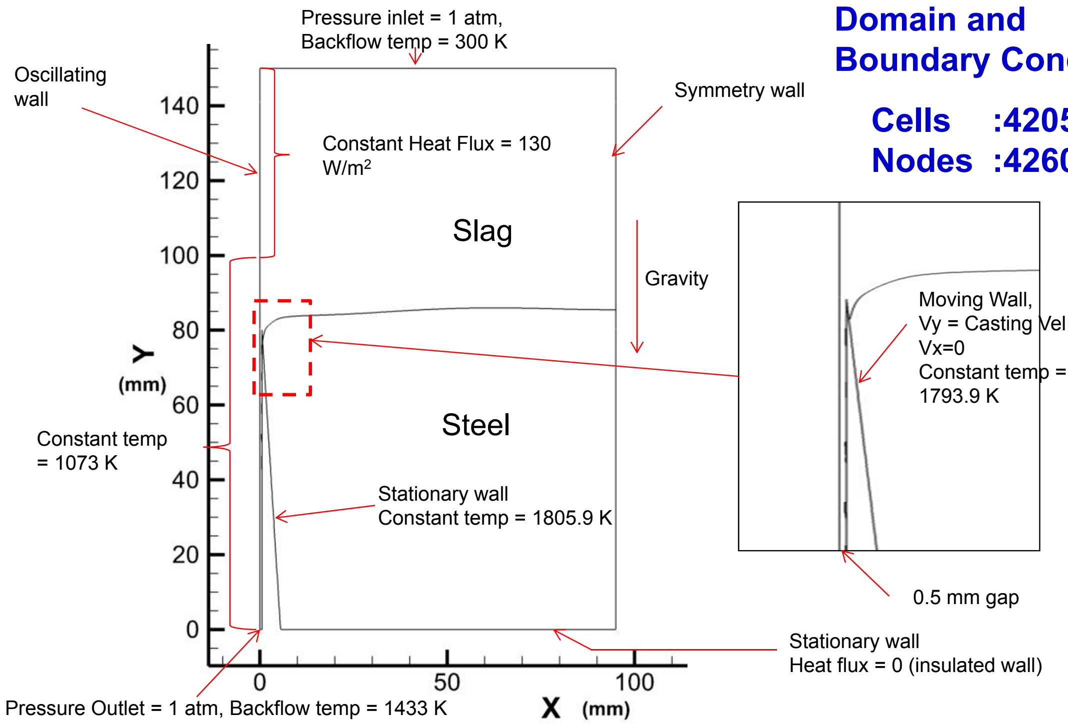


Consumption



- Gravity becomes important for very large gaps, (>1mm for this case) leading to liquid slag downward velocity exceeding casting speed.

Meniscus Region CFD Model



Domain and Boundary Conditions

Cells :42050
Nodes :42606

Model Description (Fluent)

Equations to solve–

1. **Fluid Flow**
   Realisable k-ε Model - Standard Wall functions

2. **Heat Transfer**
   Transient 2-D conduction

3. **Interface between Slag and molten Steel**
   VOF Model – Explicit Scheme (2 non-interpenetrating phases)
   - Surface Tension
   - Wall Adhesion Model

Pressure-Velocity Coupling – PISO is recommended for Transient VOF
Geo-Reconstract for surface tracking performs better.
For Pressure Interpolation Scheme PRESTO! is recommended

Material Properties

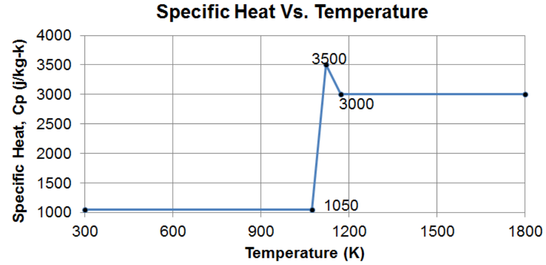
Steel Properties

- Constant properties for Steel
  - Density = 7000 kg/m^3
  - Specific Heat, Cp = 700 j/kg-k
  - Thermal Conductivity = 30 w/m-k
  - Viscosity = 0.0063 kg/m-s

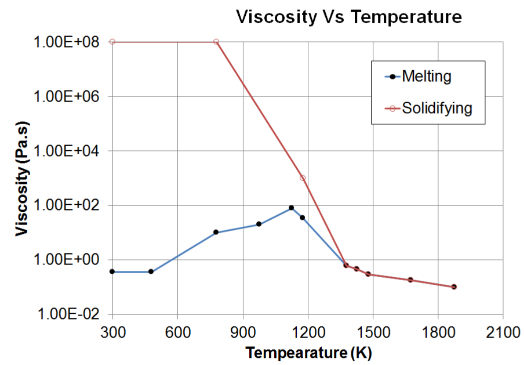
Slag Properties:

- Density = 2500 kg/m^3

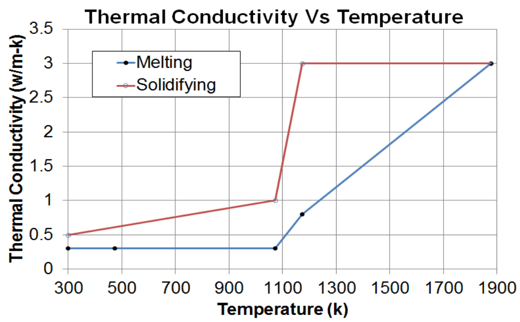
Slag: Specific Heat[1]



Slag: Viscosity[1]



Slag: Thermal Conductivity[1]



[1]Ojeda et al, AISTech 2007, Steelmaking Conference Proc., (May 7-10, Indianapolis, IN), AIST, Warrendale, PA, Vol. 1, 2007

Surface Tension between Steel(l) and Slag(l)

Surface tension of Steel(l) based on Sulphur Content[1] - **S** (0.01~0.012%)* ≈ 1600 mN/m
Surface tension of slag[2] = 431 mN/m

Using Girifalco and Good's approach[3]

$$\gamma_{steel(l)-slag} = \gamma_{steel(l)-gas} + \gamma_{slag-gas} - 2\Phi(\gamma_{steel(l)-slag} \times \gamma_{slag-gas})^{0.5}$$

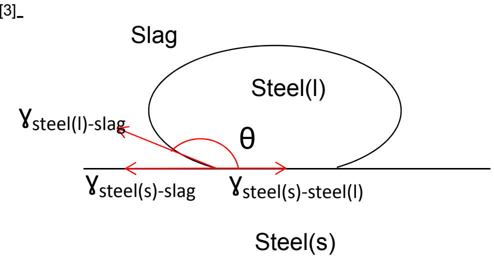
Here, Φ = 0 when there is no interactions between the phases and increases as the attraction between the phases increases.

For CaO-Al_2O_3-SiO_2 ternary system Φ is given by the relation[3]-

$$\Phi = 0.003731(\%Al_2O_3) + 0.005973(\%Si0_2) + 0.005806(\%CaO)$$

$\Phi = 0.4638$

$\boxed{\gamma_{metal(l)}\text{-slag} = 1260.7 \text{ mN/m}}$

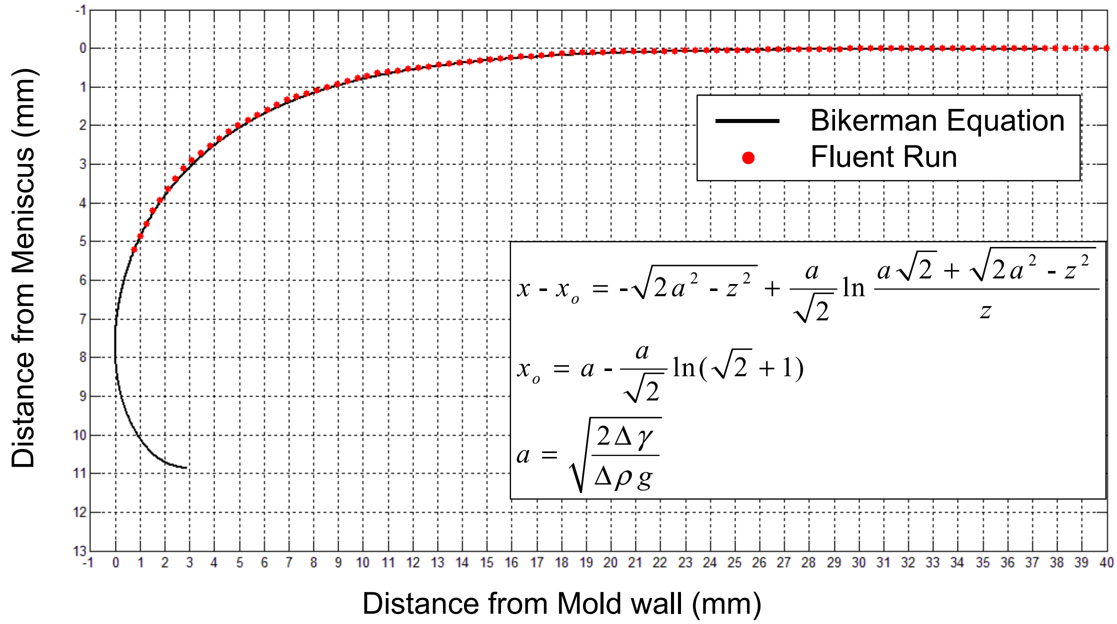


From Ojeda's[4] work,
θ~160°

[1] Ho-Jung SHIN et al, ISIJ International, Vol. 46 (2006), No. 11, pp. 1635–1644
[2] Joonho LEE and Kazuki MORITA, ISIJ International, Vol. 42 (2002), No. 6, pp. 588–594.
[3] Cramb, A W and Jimbo, Iron Steelmaker. Vol. 16, no. 6, pp. 43-55. June 1989
[4] Ojeda, CCC Annual Meeting, June 1, 2005

Validation with Bikerman Equation

- Equilibrium meniscus shape is determined by the balance of surface tension and gravity forces given by Biker-man's[1] equation –



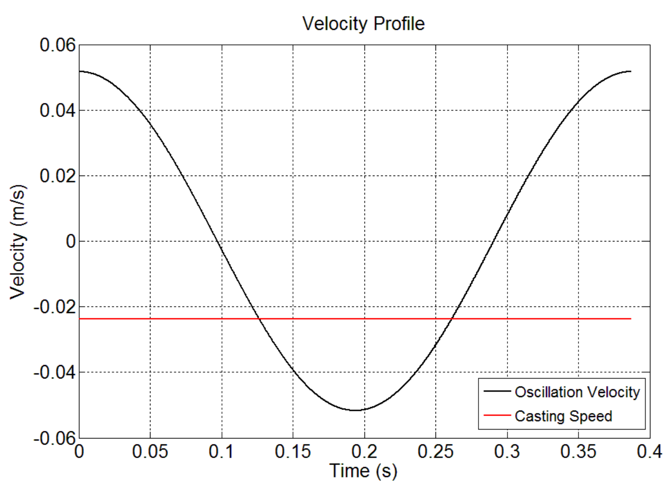
[1] J. J. Bikerman: Physical Surfaces, Academic Press, Inc., New York, (1970)

Comparison With Previous Results By Ojeda

A previous simulation by Ojeda[1] is used to compare model -

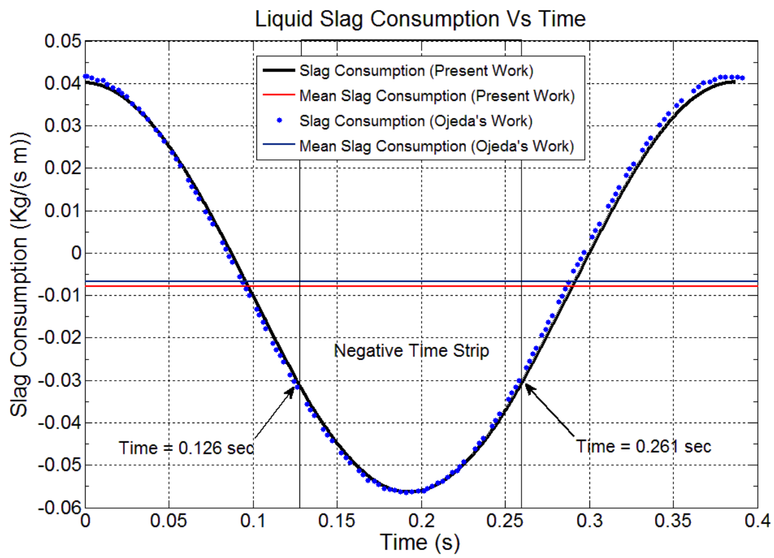
Casting Conditions:

Casting Velocity = 1.42 m/min
Stroke = 6.37 mm
Frequency = 155 cpm
Sinusoidal Oscillation



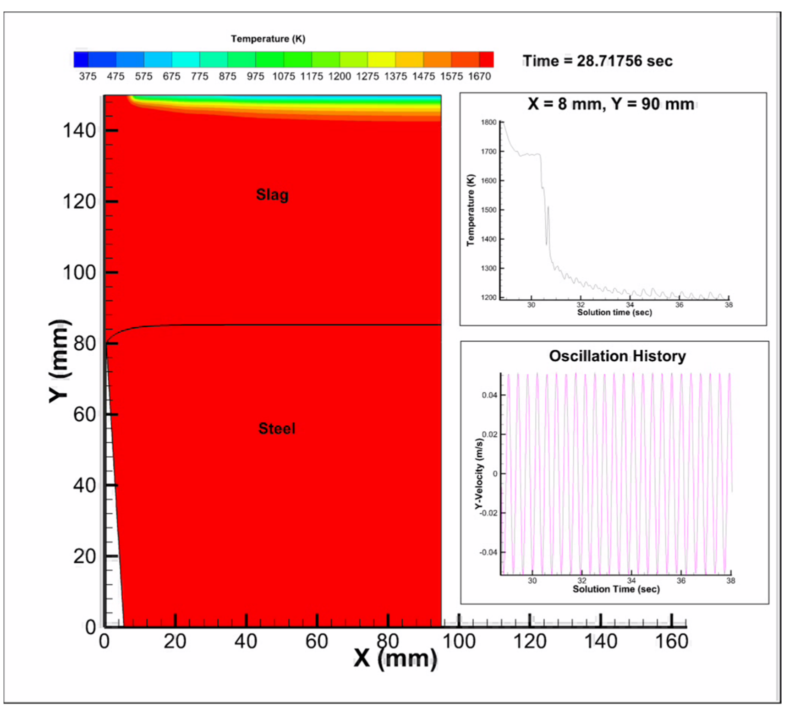
[1] Claudio Ojeda, CCC Annual Report 2006

Comparison With Previous Results By Ojeda



Mean Consumption from Ojeda's work = **0.0068 kg/(s.m)**
Mean Consumption in Present work = **0.0079 kg/(s.m)**

Simulation Animation

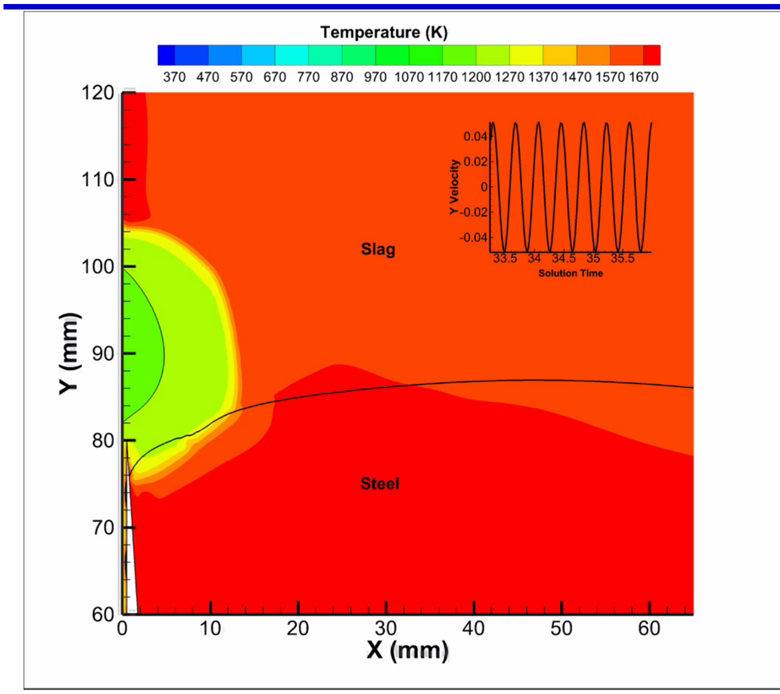


Step 1 (t=0 sec)
18 secs fluid + VOF
No movement of wall

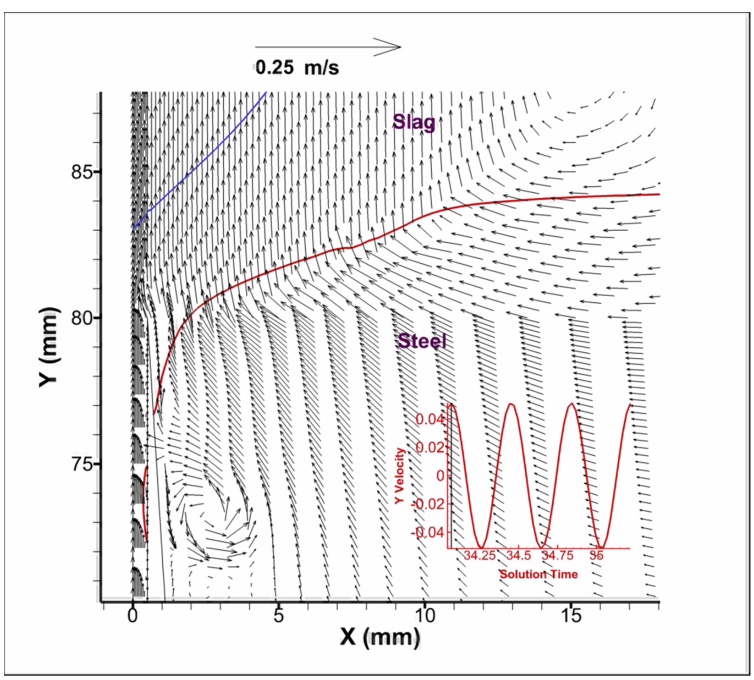
Step 2 (t=18 sec)
10 secs Casting velocity +
Mold movement applied

Step 3 (t=28s)
Coupled flow with Heat transfer

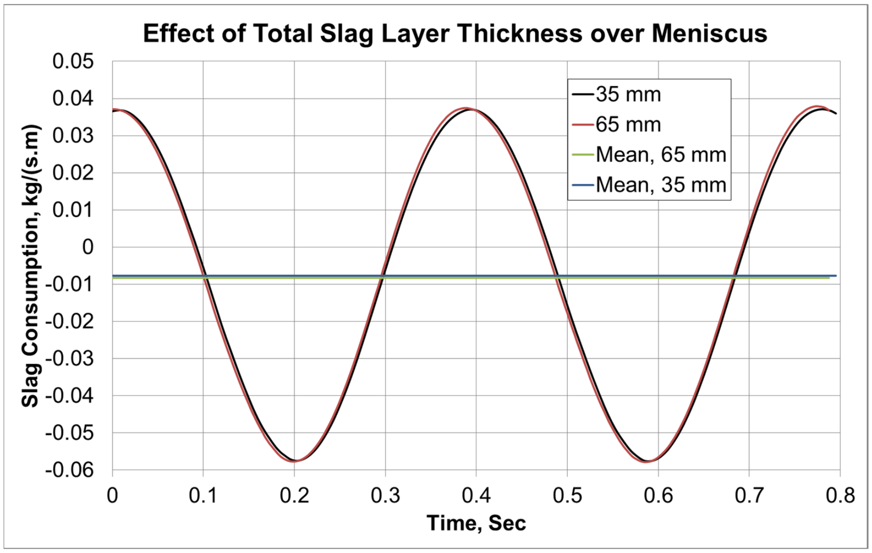
Slag Rim -Temperature



Velocity



Effect of Slag Layer Thickness Over the Meniscus



Mean Slag Consumption, 65 mm = 0.0079 kg/(s.m)
35 mm = 0.0076 kg/(s.m)

Less pressure head of slag lowers driving force for consumption (very slight effect)

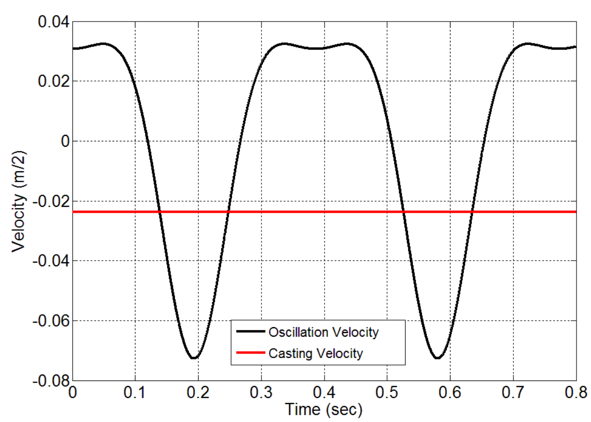
Non-Sinusoidal Oscillation

Casting Conditions:

Casting Velocity = 1.42 m/min
Stroke = 6.37 mm
Frequency = 155 cpm
Non-Sinusoidal Oscillation
Modification Ratio = 24%

Slag Property:

Conductivity - Model 1
Viscosity - Model 1



Eqn for Non-sinusoidal Oscillation*

$$y = a\sin(2\pi ft - A\sin 2\pi ft)$$

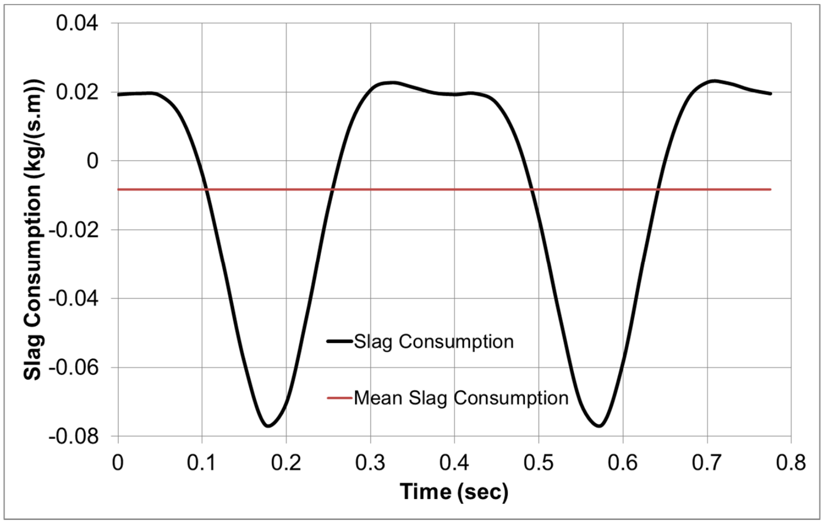
$$v = a \times 2\pi f \times (1 - A\cos(2\pi ft))\cos(2\pi ft - A\sin 2\pi ft)$$

Where,

a = stroke/2 and $A = \dfrac{4\pi\alpha}{8-\pi^2\alpha^2}$

*Xin Jin, Tingzhi Ren, A New Non-Sinusoidal Oscillation Waveform for Continuous Casting Mold, Advanced Materials Research Vols. 154-155 (2011) pp 334-337.

Slag Consumption in Non-Sinusoidal Oscillation



Mean Slag Consumption with **24% Modification Ratio = 0.0085 kg/(s.m)**

Slag Consumption increased with non-sinusoidal oscillation which matches the behavior described in literature*.

*M. SUZUKI, H. MIZUKAMI, T. KITAGAWA et al, ISIJ Int., 1991, 31, 245-261

Conclusions

- CON1D predicted correct parameters for the casting condition supplied.
- Slag layer thickness measured from plant samples was greater than predicted because they were relatively near to the corner.
- An additional slag consumption model for CON1D is being developed to correctly predict the corner region.
- CFD meniscus model using Fluent is correctly predicting the slag consumption change with change of oscillation parameters and top slag pool thickness.
- More work is needed to improve the meniscus model:
  - Temperature dependent properties for steel to make the slag consumption prediction better
  - Extend gap over the length of the mold
  - Improve accuracy of heat flux boundary to mold wall.

Acknowledgements

- Nippon Steel Corporation for plant data and helpful discussions.
- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Tata Steel, Goodrich, Magnesita Refractories, Nippon Steel Corporation, Nucor Steel, Postech/ Posco, SSAB, ANSYS-Fluent)