MechSE

CCC Annual Report

UIUC, August 19, 2015

Thermo-Fluid Modeling of the Nail Board Experiment in the Continuous Casting Process using FLUENT

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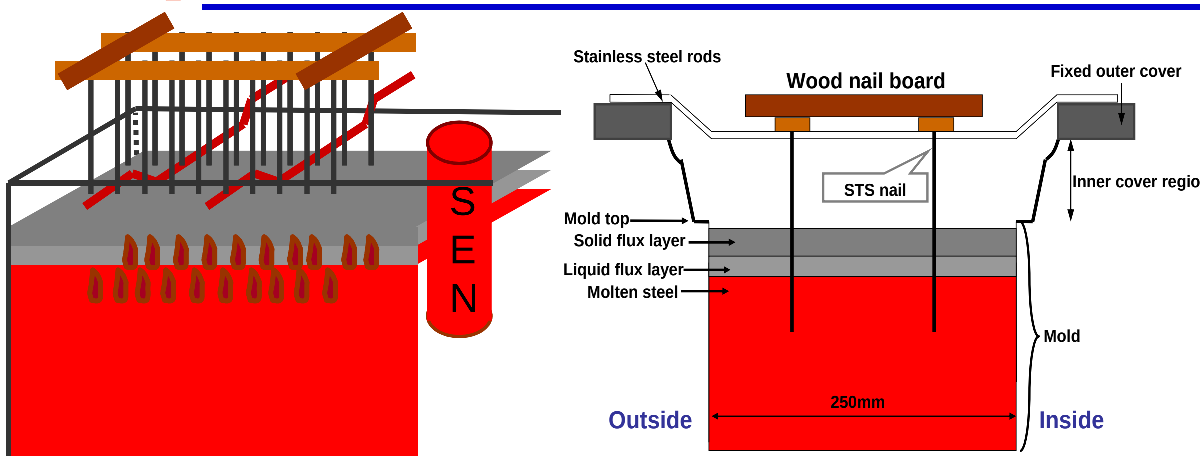
Nail Board Measurement in slab casters

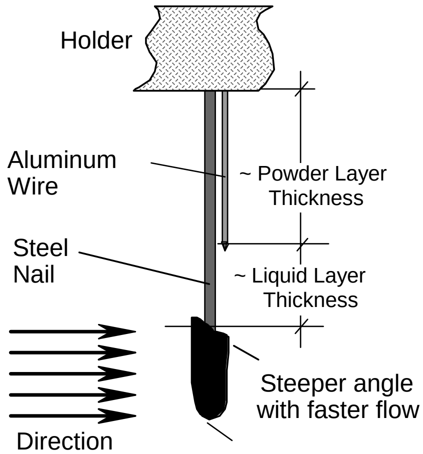


< WF View > < NF View >

- The nail is inserted into the surface of the steel. The molten steel builds up on the leading edge and decreases on the opposite side.
- The molten steel freezes to form a lump.
- The variation in temperature on the steel nail gives rise to tempering colors.

Dauby et al, LTV Steel, 1985; SM-Cho et al, TMS, 2011 [1]

Flow measurements in the caster



Interface profiles
(Nail board measurement)

Lump formed on a steel nail

- The steel nail can be used to determine the direction (angle) and velocity of the flow in the molten steel as well as the slag-steel interface.
- An aluminum wire can be used to predict the approximate liquid flux layer thickness.

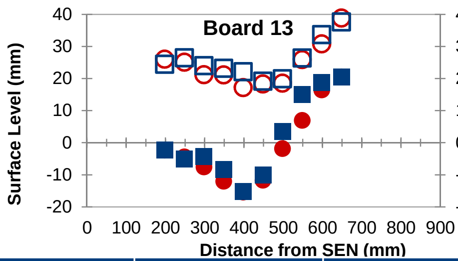
McDavid & Thomas, Met Trans, 1996, 27(4) 672-685 [2]

Objectives

- Develop a FLUENT model to simulate the dipping of a nail in the mold of the continuous casting process.
- Verify the accuracy of the model by comparing with the experimental results. Specifically: use tempering colors of steel scale observed on the nails.
- Simulate for steel, aluminum and copper nails.
- Predict a suitable methodology to predict the liquid flux layer thickness using the nail board experiment.

Nail Board Data from Severstal Experiment

Board 7
(Severstal)



Legend

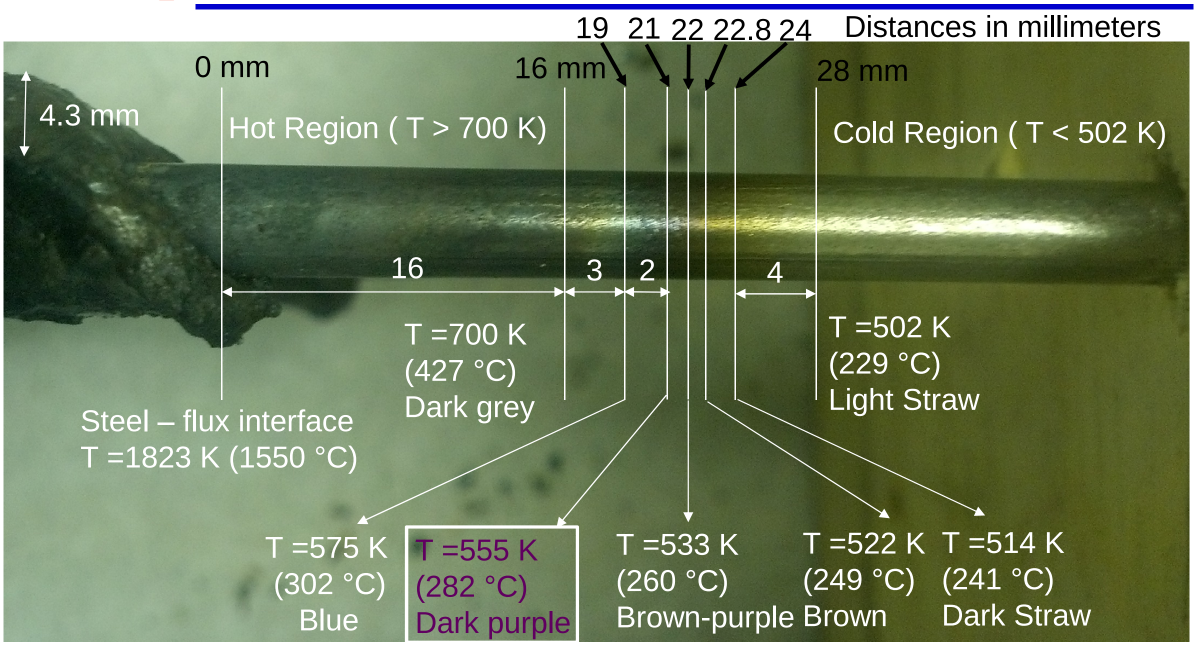
- Lump (IR)
- Discoloration (IR)
- Lump (OR)
- Discoloration (OR)

Casting Conditions for Board 13

Nail Board No.	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
13	65.0	54.99	7.0	18.07	222

Nailboard Measurements of Surface Flow at Severstal, Mihir Chavan,CCC Annual Report 2013 [3]

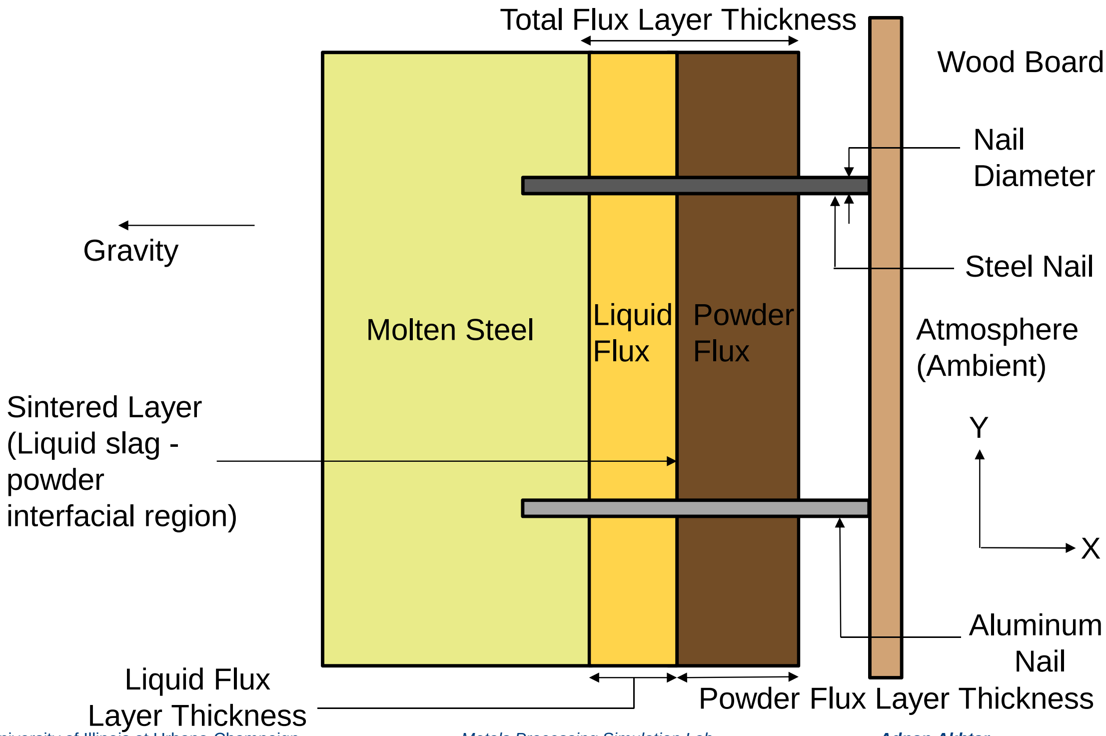
Temperature along the nail (Severstal experiment)



Discolored boundary temperature = 555 K

Image from Experiments conducted by Liu et al, Oct. 14-15, 2012 at Severstal [4]

Schematic of the Nail-Board Experiment



Calculating effective powder thermal conductivities: Equations

- The effective powder thermal conductivity is calculated using the following equation:

$$k_{eff} = \left(\left(\frac{1 - g^{\frac{1}{3}}}{k_{sol}} \right) + \left(\frac{g^{\frac{1}{3}}}{\left(1 - g^{\frac{2}{3}}\right) k_{sol} + g^{\frac{2}{3}} k_{gas}} \right) \right)^{-1}$$

  - k_{eff} is the effective powder thermal conductivity
  - k_{sol} is the solid slag thermal conductivity
  - k_{gas} is the thermal conductivity of the gas (Air)
  - g is the volume fraction of gas
- The volume fraction of the gas is calculated from the apparent density of the powder (ρ_{app}):

$$g = 1 - \frac{\rho_{app}}{\rho_{sol}}$$

Combustion of Carbon in Casting Powder in a Temperature Gradient, Supradist *et al,* ISIJ International, 2004 [5]

Calculating effective powder thermal conductivities: Values

Property	Value
k_{sol} (solid slag thermal conductivity)	2 W/m K
k_{gas} is the thermal conductivity of the gas (Air)	2.624 x 10^{-2} W/m K
ρ_{sol} (Slag density)	2600 $\mathrm{kg/m^3}$
ρ_{app} (Apparent density)	800 $\mathrm{kg/m^3}$ (300 K) 1400 $\mathrm{kg/m^3}$(1273 K)

Variable	Calculated Value	
Temperature	300 K	1273 K
g	0.70	0.48
k_{eff}	0.48 W/m K	0.90 W/m K

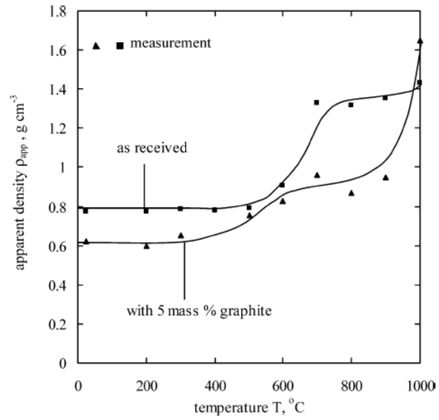


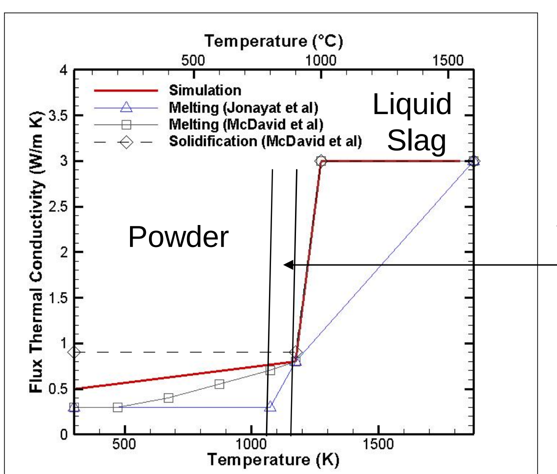
Fig. A1. Apparent density of as-received casting powder and casting powder with 5 mass% graphite, as a function of temperature.

Combustion of Carbon in Casting Powder in a Temperature Gradient, Supradist *et al,* ISIJ International, 2004 [5]
H. W. Russel: *J. Am. Ceram. Soc.*, **18** (1935) [6]

Slag Thermal conductivity variation with Temperature

- The powder thermal conductivity is 0.5 W/m K at 300 K and increases linearly to 0.8 W/m K at 1173 K.
- The liquid slag thermal conductivity is taken to be 3 W/m K.

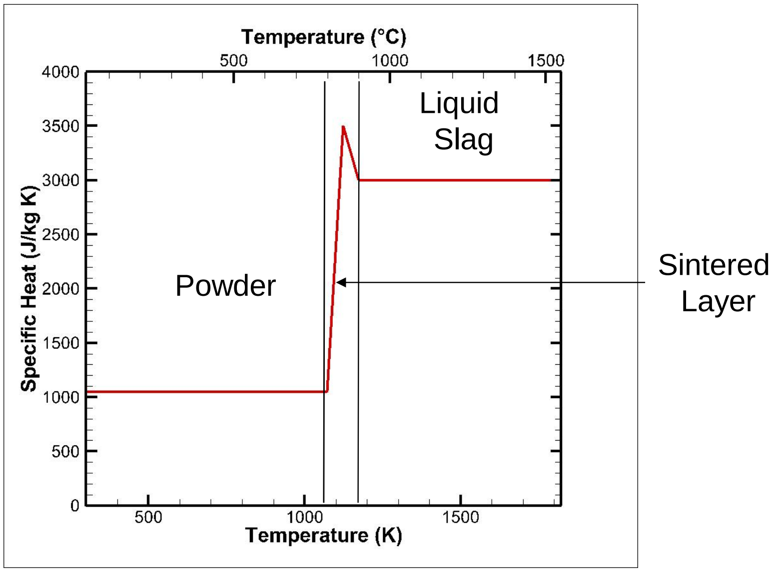
Slag / sintered layer temperature used to define liquid slag thickness is 1173 K (900 °C)



Transient Thermo-Fluid Model of Meniscus Behavior and Slag Consumption in Steel Continuous Casting, Jonayat *et al*, Metallurgical and Materials Transactions B, 2014 [7]
McDavid & Thomas, Met Trans, 1996, 27(4) 672-685 [2]

Slag Specific Heat variation with Temperature

- Slag Specific Heat variation with Temperature



Transient Thermo-Fluid Model of Meniscus Behavior and Slag Consumption in Steel Continuous Casting, Jonayat *et al*, Metallurgical and Materials Transactions B, 2014 [7]

Calculation of Flux Consumption : Equations

- The flux consumption can be determined from the empirical relation developed by Shin *et al*:
- Oscillation Mark Consumption per cycle = q_{OM} (g/m cycle)
- Lubrication Consumption per cycle = q_{lub} (g/m cycle)
- $q_{OM} = 2.5\ x\ 10^{-2} x\ \rho_{slag}\ x\ k^{1.43}\ x\ t_n^{0.389}\ x\ v_s^{-1.49}\ x\ (\sqrt{\frac{2\,\Delta\gamma}{\Delta\rho\ g}})^{0.556}$
- $q_{lub} = 0.507\ e^{(3.59\ x\ t_P)}$
  - ρ_{slag} = density of slag (kg/m^3)
  - k = empirical constant
  - tp = Positive strip time (s)
  - tn = Negative Strip Time (s)
  - vs = casting speed (mm/s)
  - $\Delta\rho$ = Density difference between liquid slag and steel
  - $\Delta\gamma$ = Surface tension difference between liquid slag and steel (N/m)

Measurement and Prediction of Lubrication, Powder Consumption, and Oscillation Mark Profiles in Ultra-low Carbon Steel Slabs, Shin *et al*, ISIJ International, 2006 [8]

Calculation of Downward Velocity in the Flux Layer: Equations

- The negative strip time is calculated using:

$$t_n = \frac{1}{\pi\, f\,(\frac{cycles}{s})} \cos^{-1}\left(\frac{v_s\,(\frac{mm}{s})}{\pi\, s\,(mm)\, f\,(\frac{cycles}{s})}\right)$$

$$t_P = T - t_n$$

- Where f = oscillation frequency, s = stroke of oscillation, T = total cycle time
- Total flux consumption per cycle (g/m cycle)= $q_C = q_{OM} + q_{lub}$
- Total Flux consumption per second per unit length (g/m s) = $q_S = q_C \times f$
- Total flux consumption (g/s) = $q_{t\_T} = q_S$ x slab perimeter = q_S x 2(slab thickness + slab width) = q_S x 2 (t + w)
- Velocity (mm/s) = $\frac{q_{t\_T}}{Slab\ Area\ \times \rho_{slag}}$
- Total Powder Flux consumption per unit area (kg/m^2) = Q = $q_C\, \frac{f}{v_s}$

AIST Continuous Casting: A Practical Training Seminar, Brian G. Thomas, Indianapolis, IN, Oct 2014 [9]

Parameters used for flux consumption determination

Parameter	Value
ρ_{slag} (Density of slag)	2600 kg /m^3
$\Delta\rho$ (Density difference between slag and steel)	4527 kg/m^3
Vs (Casting Speed)	27.5 mm/s
k (Empirical Constant depends on powder composition)	12
$\Delta\gamma$	1.3 N/m
Frequency of mold oscillation	2.9 Hz
Stroke of oscillation	6 mm
Slab Thickness	0.203 m
Slab Width	1.7 m
Positive Strip Time	0.23 s
Negative Strip Time	0.11 s

Measurement and Prediction of Lubrication, Powder Consumption, and Oscillation Mark Profiles in Ultra-low Carbon Steel Slabs, Shin *et al*, ISIJ International, 2006 [8]
Nailboard Measurements of Surface Flow at Severstal, Mihir Chavan CCC Annual Report 2013 [3]

Assumptions used in considering consumption parameter values

- The Casting speed, slab thickness and slab width values were obtained from the experiment conducted at Severstal.
- The frequency and stroke of the mold oscillation values were taken from the work of Shin *et al*.
- The value for the empirical constant was assumed to be equal to 12. The value of the empirical constant depends on the powder composition. (Note: The empirical constants depending on the powder properties used by Shin *et al* are 15.8 for Group A flux and 14 for Group C flux)

II. Mold Powder (Trial A and B):		*III. Mold Powder (Trial C):*	
CaO (39.8%) – **SiO_2** (36.3%) – **Al_2O_3** (3.4%) – **MgO** (0.8%) – **Li_2O** (0.4%) – **Na_2O** (3.4%) – **K_2O** (0.1%) – **Fe_2O_3** (0.3%) – **MnO_2** (0.03%) – **TiO_2** (0.2%) – **F** (6.0%) – **CO_2** (3.5%) – **C_{total}** (3.0%)		**CaO** (37.9%) – **SiO_2** (37.8%) – **Al_2O_3** (5.0%) – **MgO** (2.0%) – **Li_2O** (0.9%) – **Na_2O** (3.8%) – **K_2O** (0.1%) – **Fe_2O_3** (0.3%) – **MnO_2** (0.04%) – **TiO_2** (0.3%) – **F** (7.2%) – **CO_2** (3.2%) – **C_{total}** (2.6%)	
Density of liquid slag (kg m^{-3})	2680	Density of liquid slag (kg m^{-3})	2660
Viscosity at 1300 °C (Pa s)	0.321	Viscosity at 1300 °C (Pa s)	0.262
Surface tension (N m^{-1})	0.431	Surface tension (N m^{-1})	0.419
Solidification temperature (°C)	1145	Solidification temperature (°C)	1101
Melting temperature (°C)	1180	Melting temperature (°C)	1145

- The empirical constant value of 12 indicates a lower melting temperature for the slag chosen.

Measurement and Prediction of Lubrication, Powder Consumption, and Oscillation Mark Profiles in Ultra-low Carbon Steel Slabs, Shin *et al*, ISIJ International, 2006 [8]

Flux Consumption and Axial Velocity Calculated

Parameter	Value Calculated
Oscillation Mark Consumption per cycle = q_{OM} (g/m cycle)	0.47 g/m cycle
Lubrication Consumption per cycle = q_{lub} (g/m cycle) (Includes both solid and liquid slag)	1.16 g/m cycle
Total Flux consumption per cycle = q_C	1.63 g/m cycle
Total Flux consumption per second per unit length = q_S	4.71 g/m s
Total flux consumption (g/s) = q_{t_T}	17.94 g/s
Total Powder Consumption per unit area = Q	0.171 $\mathrm{kg/m^2}$
Axial Velocity of flux	**0.020 mm/s**

Calculation of Surface Heat transfer coefficient (Parameters considered)

Parameter	Value
Emissivity of Air	0.8
Ambient Temperature (Tamb)	300 K
Kinematic Viscosity of Air	1.568 x 10^{-5} m^2/s
Thermal conductivity of air	2.624 x 10^{-2} W/m K
Specific heat of air	1004.9 J/kg K
Coefficient of Thermal Expansion for air	3.35 x 10^{-3} 1/K
Slab Width	1.7 m
Slab Thickness	0.203 m

Correlations for Heat Transfer Coefficient Calculation

- The correlation for calculation of heat transfer coefficient is based on natural convection over a rectangular plate of known dimensions (McAdam's correlation).
- The Convective Heat Transfer coefficient is calculated using the empirical relation:

  $Nu = 0.14\ Ra^{0.33}$ for $Ra = 2 \text{ x } 10^7 - 3 \text{ x } 10^{10}$

  Where Ra is the Rayleigh number.

$$Ra = \frac{\rho g \beta \Delta T\ L^3}{\mu \alpha}$$

  - Characteristic length = L = average of the slab width and slab thickness

$$h_{con} = Nu\ \frac{k_{air}}{L}$$

- The Heat Transfer coefficient for radiation is calculated using:

$$h_{rad} = \sigma \varepsilon (To^4 - Tamb^4)$$

W.H. McAdams, Heat Transmission, 3rd ed, McGraw Hill, 1954 [10]
Convective Heat Transfer, Louis C Burmeister (Pg 550) [11]

Heat Transfer Coefficient Calculation for surface temperature = 580 K

- To = Surface Temperature = 580 K
- Using properties of air: Ra = 2.26 x 10^{10}
- Nu = 362.0
- **Average heat Transfer coefficient = 10.0 W/m^2 K**

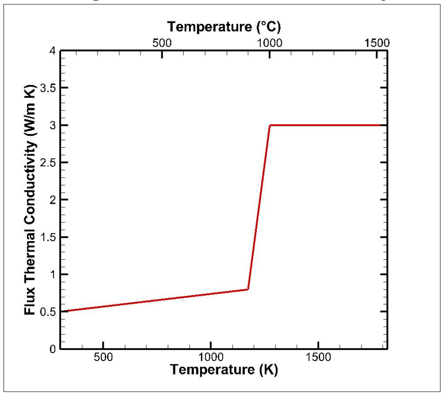
- Ambient Temperature = 300 K
- **Heat Transfer coefficient for radiation= 17.0 W/m^2 K**

- **Total Heat Transfer Coefficient = 17.0 + 10.0= 27 W/m^2 K**

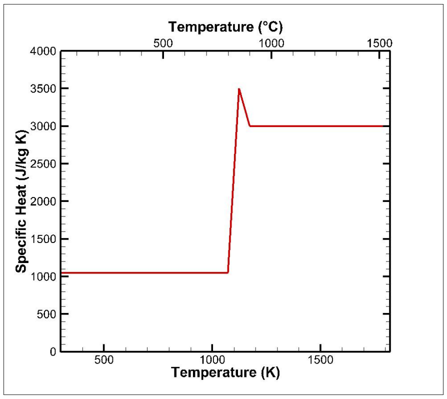
Transient Behavior in the Flux Layer (Simulation Parameters)

Parameter	Value
Slag Density	2600 kg/m^3
Total Flux Layer Thickness	40 mm
Ambient Temperature	300 K
Surface Heat Transfer Coefficient (Surface Temperature = 580 K)	27 W/m^2 K

Slag Thermal Conductivity

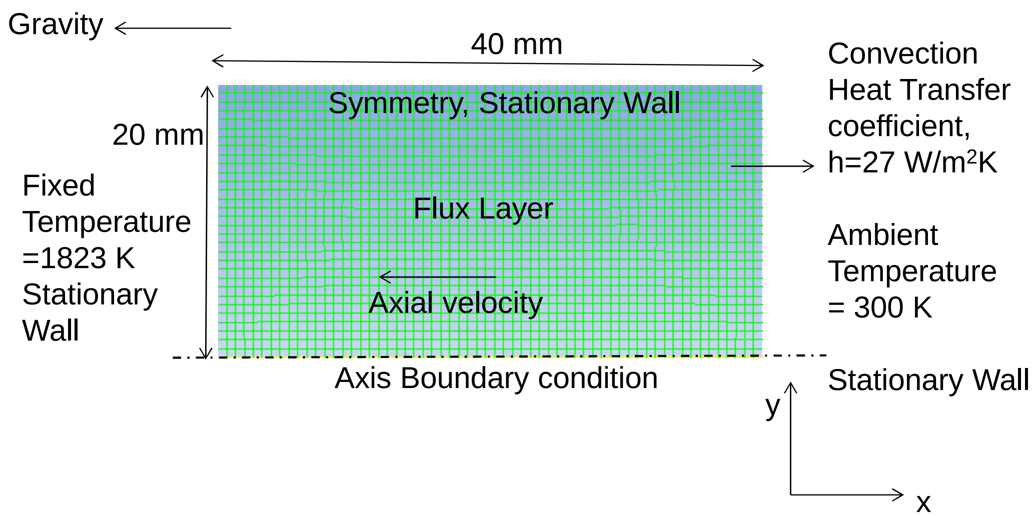


Slag Specific Heat



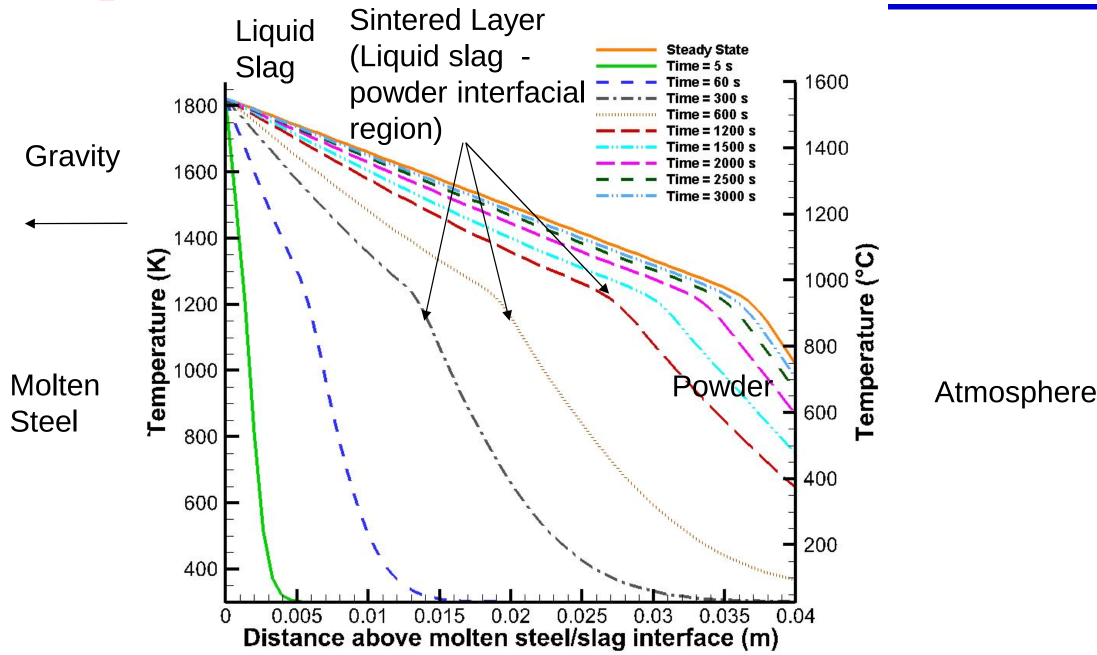
Mesh and Simulation Conditions (no nail)

Minimum element length = 0.6 mm



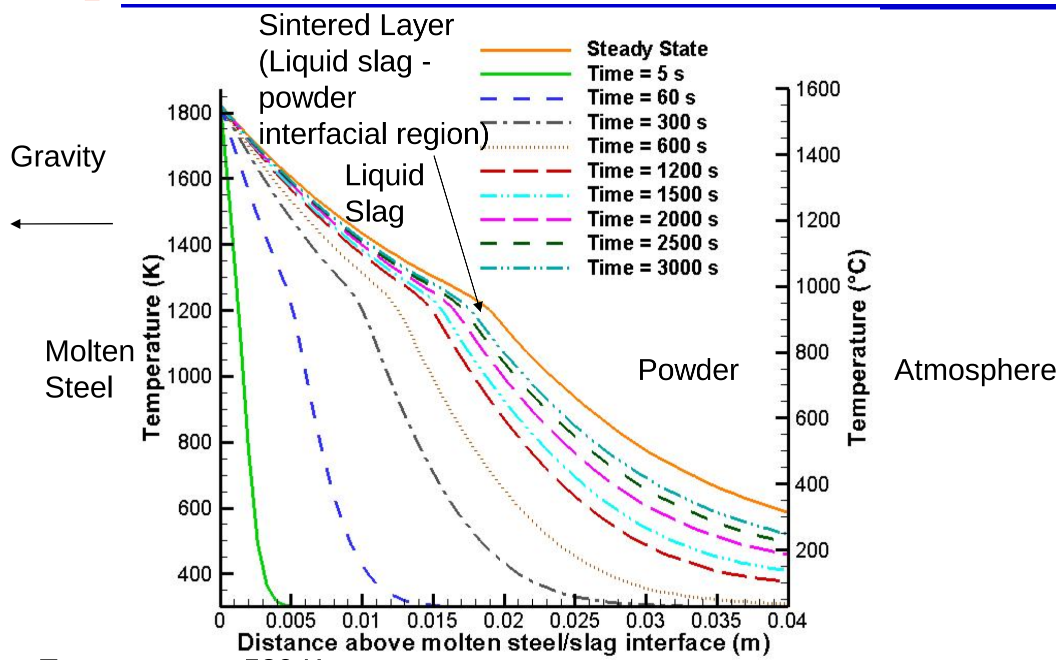
Initial Condition: The temperature in the entire domain is at 300 K.
An axial velocity is defined in the entire domain calculated from the flux consumption.
Time step size chosen for the simulation = 0.05 s, Maximum Iterations per time step = 20
Only the energy equation is solved.

Temperature at different times in the flux layer for no consumption



Surface Temperature = 1020 K
Heat Transfer Coefficient = 68 W/m^{2}K

Temperature at different times in the flux layer for consumption = 4.71 g/m s

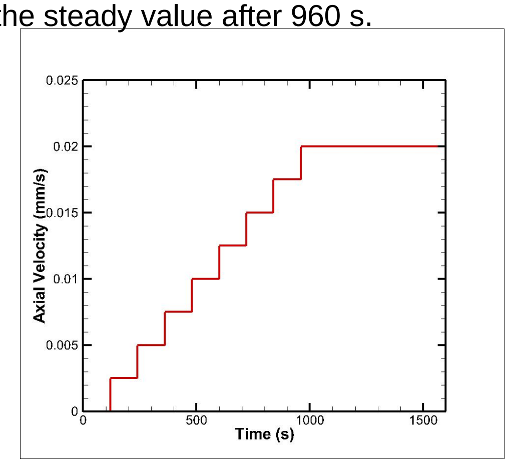


Surface Temperature = 580 K

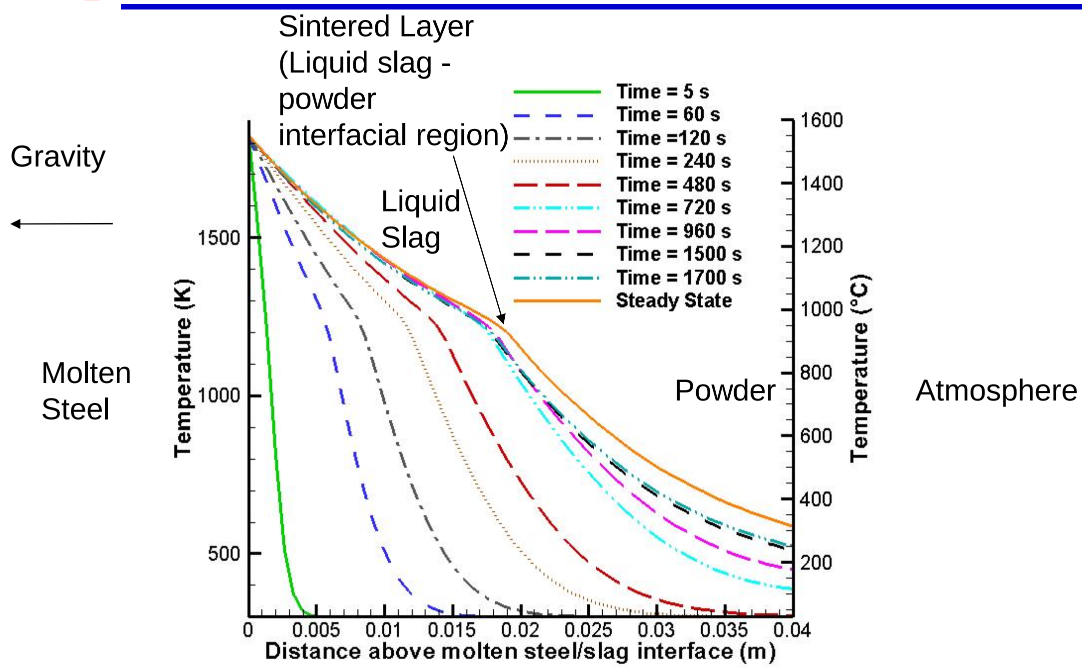
Heat Transfer Coefficient = 27 W/m^{2}K

Increasing Flux Consumption with time

- The transient simulation is based on an increasing flux consumption (axial velocity) with time.
- Initially, there is only powder in the flux layer and no flux consumption. As the powder heats up, it melts to form the liquid slag layer. The growth of the liquid slag layer results in an increase in the flux consumption.
- Thus, the consumption increases from 0 to a steady value of 4.71 g/m s (0.02 mm/s). For this simulation, the consumption is increased in steps after every 120 s until it reaches the steady value after 960 s.



Temperature at different times in the flux layer for increasing flux consumption



Surface Temperature = 580 K
Heat Transfer Coefficient = 27 W/m^2K

Inferences from the transient behavior in the flux layer

- Initially the entire layer is composed of only powder flux. With increasing time the powder melts to form the sintered and the liquid flux layer. The liquid layer thickness increases until the heat from the molten steel equals the heat loss to the atmosphere.
- The change in slope (kink) observed in the temperature plot is at the liquid slag-powder interfacial (Sintered) region. The slope change is due to high-thermal conductivity liquid slag dropping to low-conductivity powder.
- A higher consumption lowers the temperature in the slag greatly.
- The increasing consumption with time reaches steady state in a shorter time than with either the no consumption or constant consumption case.

Continuous Casting Consortium

Heat Transfer with slag consumption in the Flux Layer and Steel Nail

Continuous Casting Consortium

Tempering Colors of Steel (Tool Steel Color vs Temperature)

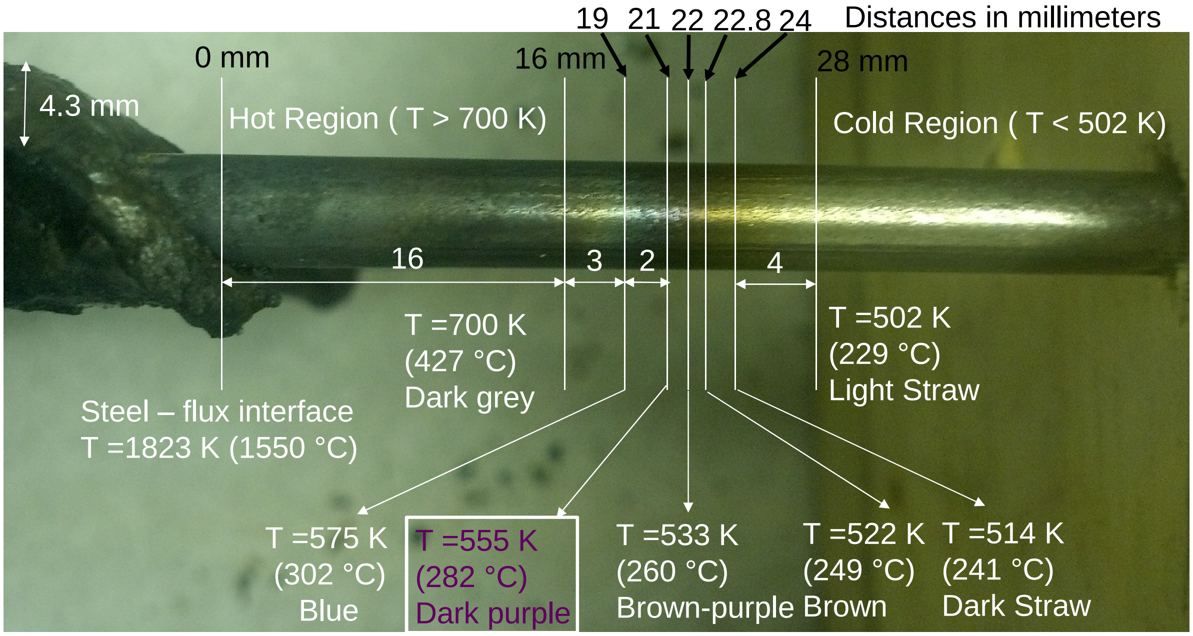
Tool Steel Color vs Temperature

2000°F	Bright yellow	1093°C
1900°F	Dark yellow	1038°C
1800°F	Orange yellow	982°C
1700°F	Orange	927°C
1600°F	Orange red	871°C
1500°F	Bright red	816°C
1400°F	Red	760°C
1300°F	Medium red	704°C
1200°F	Dull red	649°C
1100°F	Slight red	593°C
1000°F	Very slight red, mostly grey	538°C
0800°F	Dark grey	427°C
0575°F	Blue	302°C
0540°F	Dark Purple	282°C
0520°F	Purple	271°C
0500°F	Brown/Purple	260°C
0480°F	Brown	249°C
0465°F	Dark Straw	241°C
0445°F	Light Straw	229°C
0390°F	Faint Straw	199°C

threeplanes.net/toolsteel.html [12]

- It is known that the diameter of the nail used for the experiment is 5 mm.
- Using this as scale, the distances along the length of the nail can be measured using a photograph of the nail.
- The steel-flux interface is at the mean distance between the top and bottom surface of the solidified steel.
- This is due to the fact that on dipping of the nail, a wave is generated. The higher region corresponds to the side towards which the molten steel is flowing.

Temperature along the nail (Severstal experiment)



Discolored boundary temperature = 555 K

Image from Experiments conducted by Liu et al, Oct. 14-15, 2012 at Severstal [4]

Calculation of Nail Dipping Time

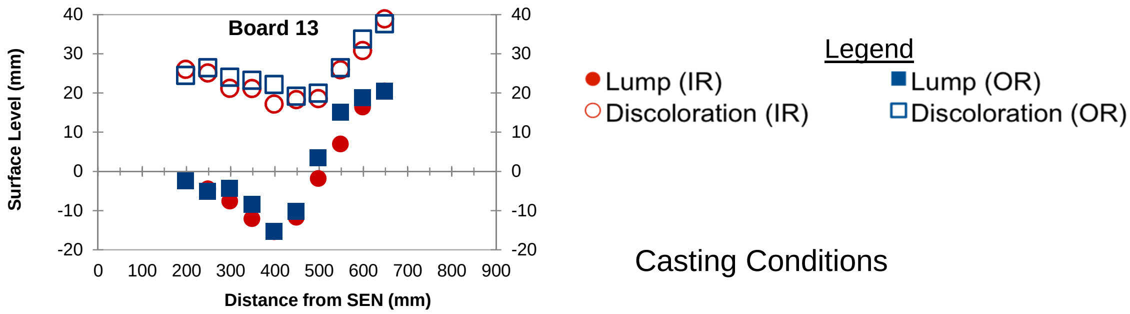
- From the image, the thickness of the lump formed on the nail is found out to be 4.3 mm.
- The solidification time for the lump is found out using the following equation:

$$s = k\sqrt{t}$$

  - s = lump thickness
  - k = 1.1 inch/$\sqrt{min}$ = 3.6 x 10^{-3} m/$\sqrt{s}$
- Solidification Time Calculated = 1.42 s
- A nail dipping time of 1.5 s was selected for the simulation. (Generally 1-3 s is the dipping time used by researchers)

Experimental data for Nail Board 13

- Nail Board 13 selected for evaluation due to variations in distance from discolored region to lump.



Casting Conditions

Nail Board No.	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
13	65.0	54.99	7.0	18.07	222

Nailboard Measurements of Surface Flow at Severstal, Mihir Chavan,CCC Annual Report 2013 [3]

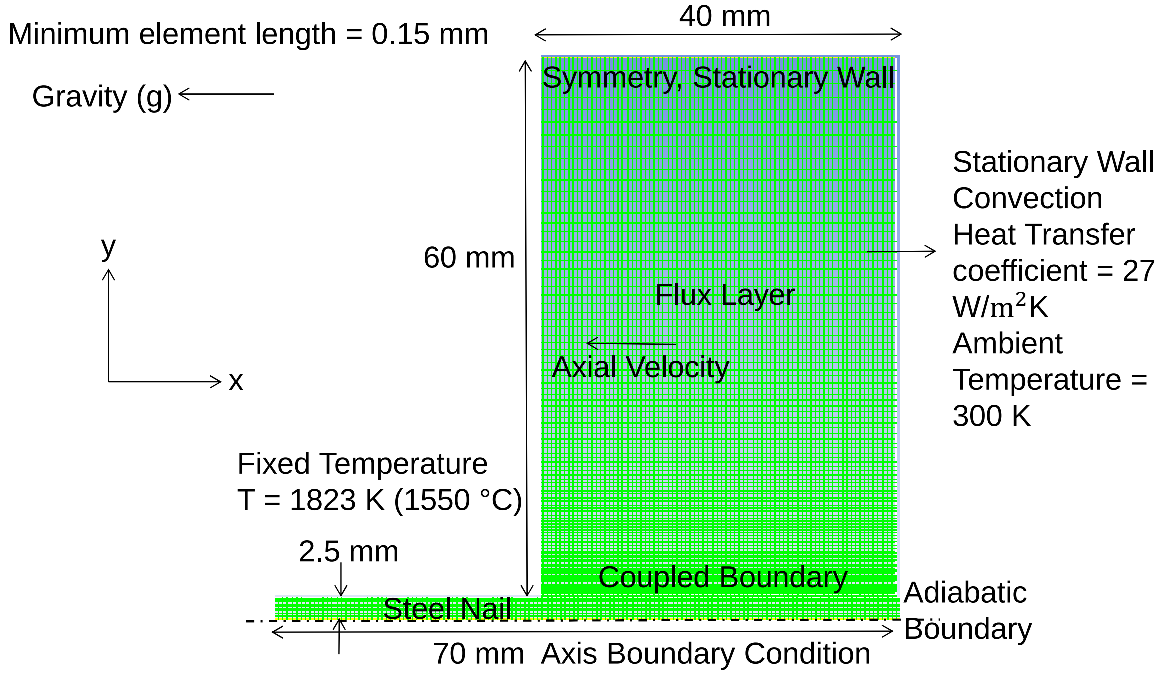
Nails selected for comparison

- The nails : 6 IR, 7 IR and 9 IR were selected for comparison with the simulation.

Nail No. from SEN → 6 IR ← Inner Radius

Nail No.	Distance of discoloration from Steel-Slag Interface (mm)	Distance of lump from Steel-Slag Interface (mm)	Distance between discoloration and lump (mm)	Total Thickness used in simulation (mm)	Powder Level from Steel-Slag interface according to simulation (mm)	Measured distance from wooden board to lump (mm)	Space between top of powder and board (mm)
9 IR	30.81	16.40	14.41	30	46.40	30	0
7 IR	19.92	-1.86	21.78	40	38.14	47	7
6 IR	19.17	-10.21	29.38	50	39.79	57	7

Mesh and Boundary Conditions for simulation with flux consumption and nail



Simulation Parameters

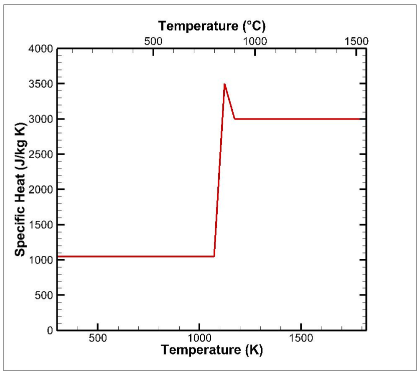
- Time Step size chosen for transient run = 5 x 10^{-3} s
- Max Iterations per time step = 20
- The Initial condition for the simulation included the steady state temperature in the flux layer and the nail at ambient temperature of 300 K.
- For including the effect of flux consumption, a constant axial velocity was defined in the entire domain.
- The simulation involved only solving the energy equation.

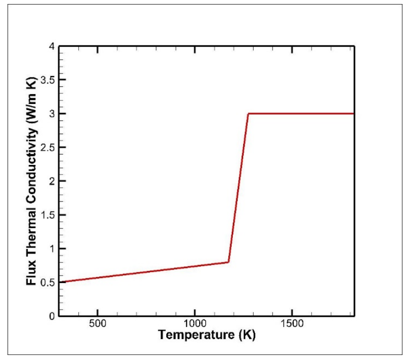
Flux and Steel Properties used in the simulation

- Slag Density = 2600 kg/m^3
- Steel Density= 8030 kg/m^3
- Steel Specific Heat = 502.5 J/kg K
- Steel Thermal Conductivity = 16.3 W/m K

Slag Thermal Conductivity
k = 0.5 W/m K at T = 300 K
Linearly increases to 0.8 W/m K
300 K < T < 1173 K
Linearly increases to 3 W/m K at 1273 K
1173 K < T < 1273 K
k = 3 W/m K, T> 1273 K

Slag Specific Heat





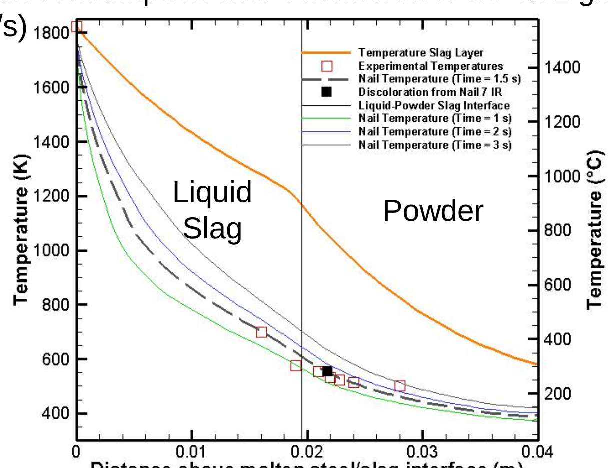
http://www.arc.vt.edu/ansys_help/flu_ug/flu_ug_biblio.html#XUGhsu-jemcov [13]

Simulation Conditions and Nail Temperature for Nail 7 IR

- Total Flux Layer Thickness = 40 mm
- Powder surface temperature = 580 K
- Surface Heat Transfer coefficient = 27 W/m^2K
- The local flux consumption was considered to be 4.71 g/m s. (Axial velocity = 0.02 mm/s)

Molten Steel

Gravity

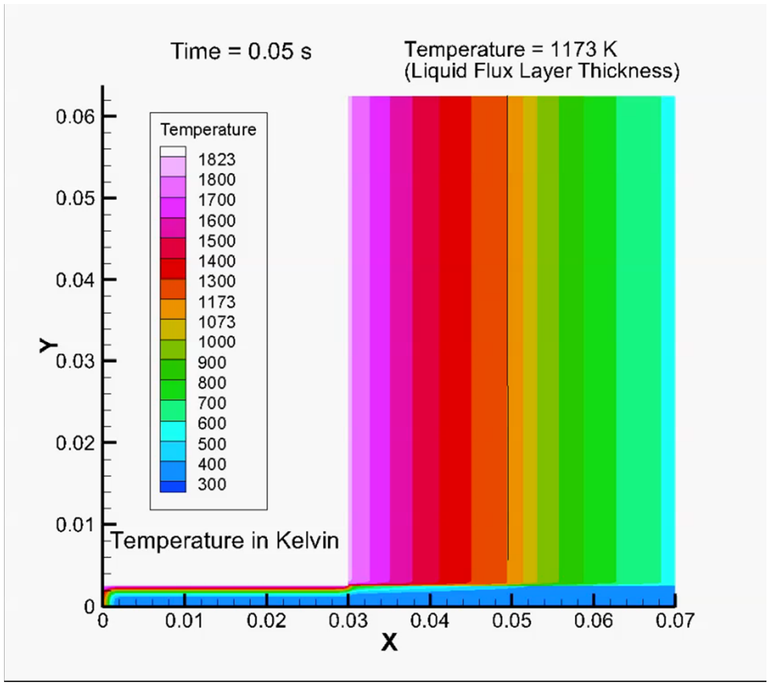


Atmosphere

The Liquid slag -Powder interface is considered at 1173 K (900 °C)
Nail Temperature at the liquid-powder interface = 609.7 K = 336.7 °C
% Liquid flux layer thickness / Distance of discoloration from lump = 89.5 %

Temperature contours with time for Nail 7 IR

Gravity



Comparison with Experimental Nail Surface Temperatures

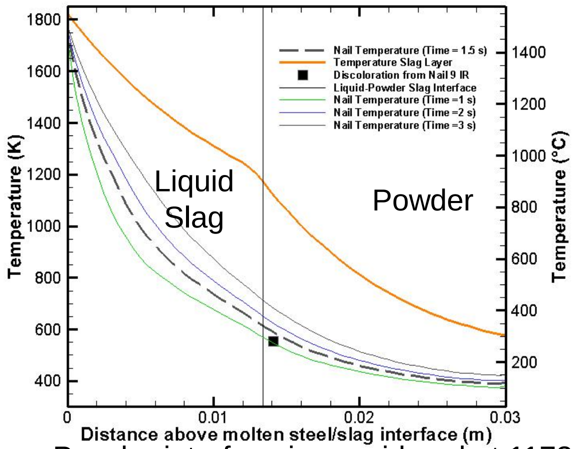
- The trend of the nail surface temperatures from the picture match the simulation after a dipping time of 1.5 s.
- The discoloration at 555 K matches with the simulation for the Nail 7 IR.
- Thus, for the other nails the discoloration points should match for the same dipping time of 1.5 s.
- The powder surface temperature is kept constant for all the simulations based on the assumption that the powder surface temperature does not change from the SEN to the narrow face.

Simulation Conditions and Nail Temperature for Nail 9 IR

- Total Flux Layer Thickness = 30 mm
- Powder surface temperature = 580 K
- Surface Heat Transfer coefficient = 27 W/m^2K
- The local flux consumption was considered to be 7.06 g/m s. (Axial velocity = 0.03 mm/s)

Molten Steel

Gravity



Atmosphere

The Liquid slag -Powder interface is considered at 1173 K (900 °C)
Nail Temperature at the liquid-powder interface = 614.5 K = 341.5 °C
% Liquid flux layer thickness / Distance of discoloration from lump = 95 %

Simulation Conditions and Nail Temperature for Nail 6 IR

- Total Flux Layer Thickness = 50 mm
- Powder surface temperature = 580 K
- Surface Heat Transfer coefficient = 27 W/m^2K
- The local flux consumption was considered to be 3.41 g/m s. (Axial velocity = 0.0145 mm/s)

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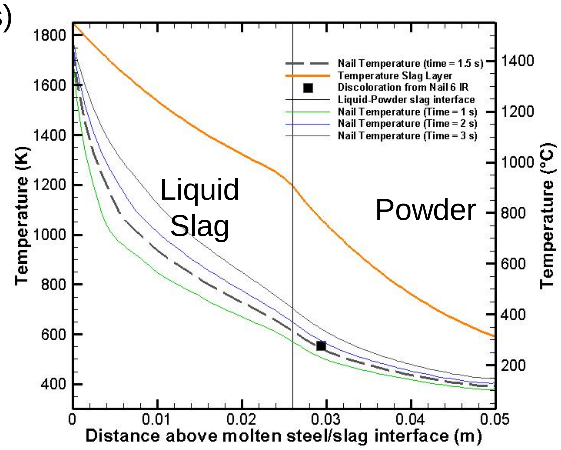


Atmosphere

The Liquid slag -Powder interface is considered at 1173 K (900 °C)
Nail Temperature at the liquid-powder interface = 613.5 K = 340.5 °C
% Liquid flux layer thickness / Distance of discoloration from lump = 88.4 %

Parametric Study using a steel nail (Effect of Nail Dipping Time)

Effect of Nail Dipping Time

Flux consumption = 4.71 g/m s (0.02 mm/s velocity),Total Slag Thickness = 50 mm

Nail Dipping Time (s)	Liquid Flux Layer Thickness (mm)	Distance of discoloration (555 K) from lump (mm)	% Liquid Flux Layer / Distance of discoloration from lump
1 s	19.0 mm	19.5 mm	97.4 %
1.5 s	19.0 mm	21.0 mm	90.5 %
3 s	19.0 mm	24.5 mm	77.5 %
4 s	19.0 mm	26.0 mm	73.0 %
5 s	19.0 mm	27.5 mm	69.0 %
6 s	19.0 mm	28.5 mm	66.7 %

Parametric Study using a steel nail (Effect of Total Flux Layer Thickness)

Effect of Total Flux Layer Thickness

Flux consumption constant = 4.71 g/m s (0.02 mm/s velocity),
Nail Dipping Time = 1.5 s

Total Flux Layer Thickness (mm)	Liquid Flux Layer Thickness (mm)	Distance of discoloration (555 K) from lump (mm)	% Liquid Flux Layer / Distance of discoloration from lump
30 mm	19.0 mm	21.0 mm	90.5 %
40 mm	19.5 mm	21.8 mm	89.5 %
50 mm	19.0 mm	21.0 mm	90.5 %

Parametric Study using a steel nail (Effect of Flux Consumption and dipping time)

Effect of Flux Consumption

Total Flux Layer Thickness = 50 mm, Nail Dipping Time = 1.5 s

Flux Consumption (g/m s)	Liquid Flux Layer Thickness (mm)	Distance of discoloration (555 K) from lump (mm)	% Liquid Flux Layer / Distance of discoloration from lump
3.41 g/m s	26.0 mm	29.4 mm	88.4 %
4.71 g/m s	19.0 mm	21.0 mm	90.5 %
7.06 g/m s	11.9 mm	13.6 mm	87.5 %

Total Flux Layer Thickness = 50 mm, Nail Dipping Time = 3 s

Flux Consumption (g/m s)	Liquid Flux Layer Thickness (mm)	Distance of discoloration (555 K) from lump (mm)	% Liquid Flux Layer / Distance of discoloration from lump
3.41 g/m s	26.0 mm	33.3 mm	78.0 %
4.71 g/m s	19.0 mm	24.5 mm	77.5 %
7.06 g/m s	11.9 mm	15.9 mm	74.8 %

Inferences from the heat transfer in a steel nail

- Average Flux consumption of the three simulations is 5.06 g/m s. The local flux consumptions average out to give approximately the total flux consumption for the process.
- Regions near the SEN have lower consumption as compared to those near the narrow face. A larger consumption is observed for a smaller total flux layer thickness.
- The discoloration temperature from the experiment match with the simulation temperature for a dipping time of 1.5 s.
- The average nail temperature at the liquid layer thickness is 340 °C. (From the tempering colors of steel, this corresponds to a transition from dark grey to blue)
- Given the uncertainty of reading dark grey, it would be more accurate to measure from the dark purple discolored band (555 K) to the lump, and adjust according to:
  - Nail Dipping Time (90 % for 1.5 s and 75 % for 3 s)
- The flux consumption and total slag layer thickness do not have a significant effect on the % Liquid flux layer thickness to distance of discoloration from lump ratio.

Heat Transfer with slag consumption in the Flux Layer and Aluminum Nail

Aluminum Properties used in the simulation

- Aluminum Density= 2719 kg/m^3
- Aluminum Specific Heat = 871 J/kg K
- Aluminum Thermal Conductivity = 202.4 W/m K
- Molten Aluminum Specific Heat = 1090 J/kg K
- Molten Aluminum Thermal Conductivity = 93-99 W/m K

http://www.arc.vt.edu/ansys_help/flu_ug/flu_ug_biblio.html#XUGhsu-jemcov [13]
http://www.engineeringtoolbox.com/ [14]

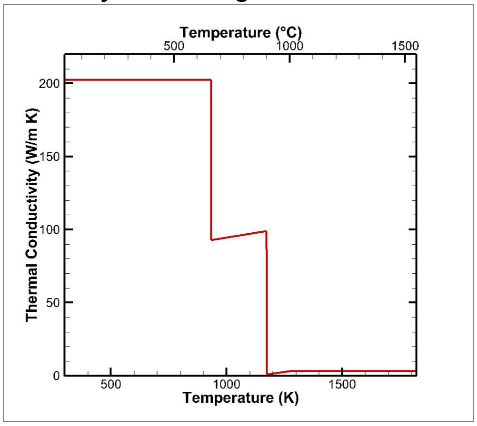
3 Aluminum nail cases: change properties/physical scenario and dipping distance

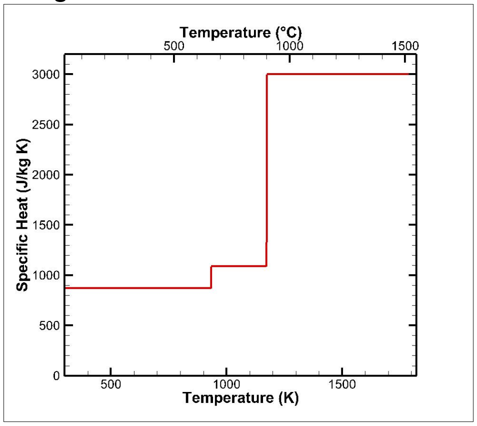
1. The Aluminum Nail remains solid (300 - 933 K) until the Al melts.
2. After the Al melts, the surrounding slag may solidify (933 – 1173 K) until the slag melts. There could be mixture of Al and slag in the column of molten material beneath the nail.
3. Above 1173 K, the powder melts to form the liquid slag. Therefore, molten Aluminum and liquid slag will co-exist above this temperature.
4. For analyzing this phenomenon, three cases are simulated:

Case 1:	Solid Aluminum properties up to the melting temperature of Aluminum 933 K (660 °C). Molten Aluminum properties up to 1173 K (900 °C). Above 1173 K, slag properties.
Case 2:	Scenario 1 dipped only in flux layer with 5mm liquid slag gap
Case 3:	Dipped only in flux layer with 5mm liquid slag gap Solid Aluminum properties up to the melting temperature of Aluminum 933 K (660 °C). Slag properties up to 1173 K (900 °C). Above 1173 K, molten Aluminum properties.

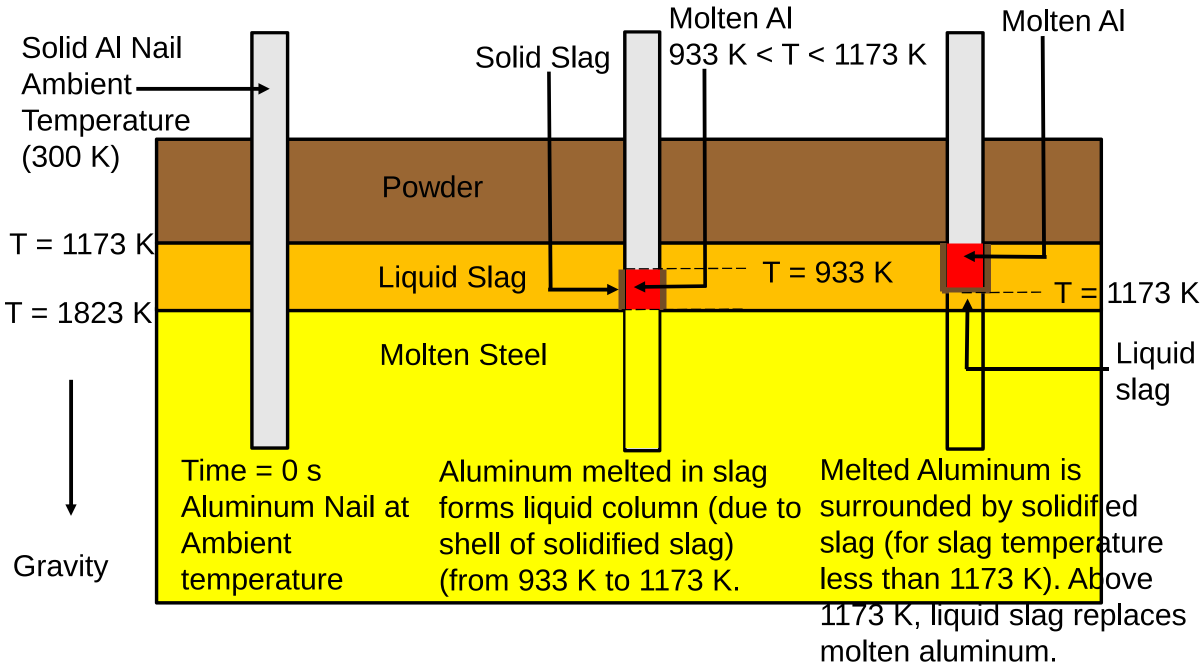
Properties defined in the nail region

1. The properties in the nail region in contact with the flux layer is defined by solid Aluminum properties up to the melting temperature of Aluminum 933 K (660 °C).
2. On melting the properties of molten Aluminum are considered until the slag melting temperature of 1173 K (900 °C).
3. Above 1173 K, slag properties are considered in the nail region.
4. Density in the region is constant = 2719 kg/m^3

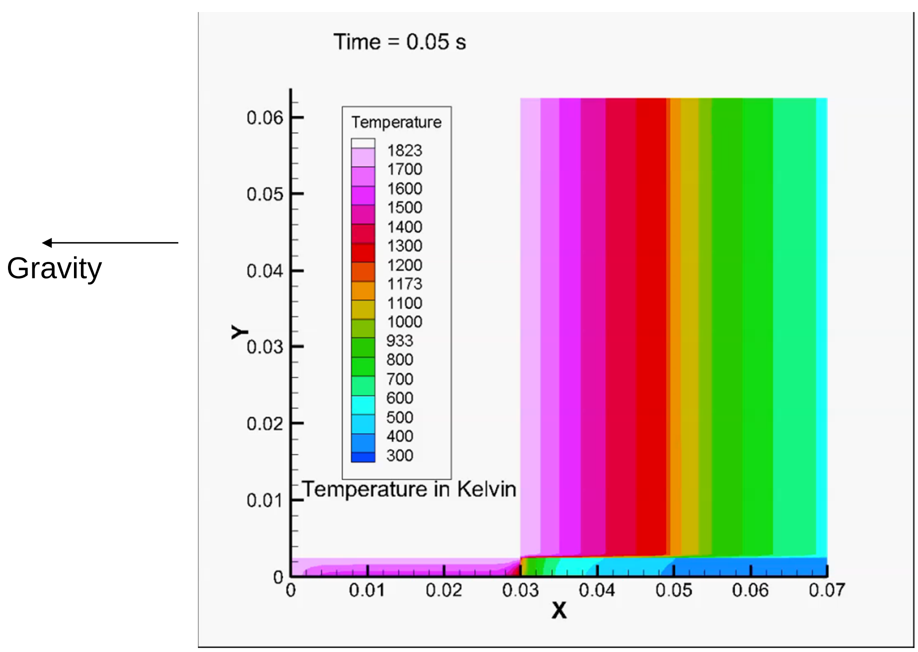




Aluminum Nail Dipping Case 1



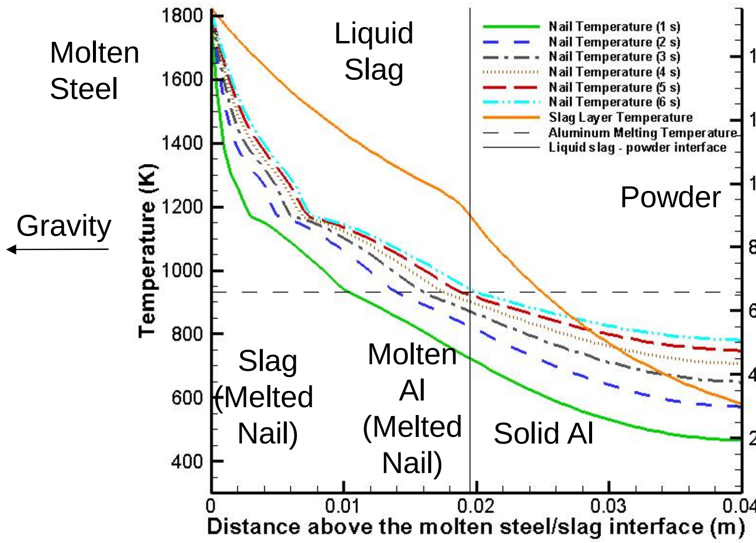
Temperature contours with time for Aluminum Nail (Case 1: Nail dipped in molten steel)

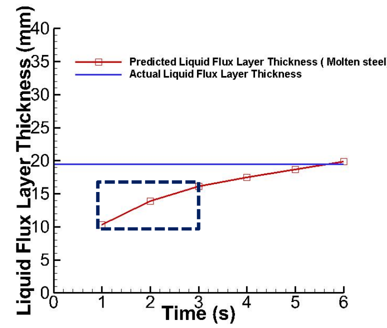


Contours at 933 K and 1173 K indicates the melting temperature of Aluminum and slag respectively.

Aluminum Nail Surface Temperature variation with time (Case 1 - Nail dipped in molten steel)

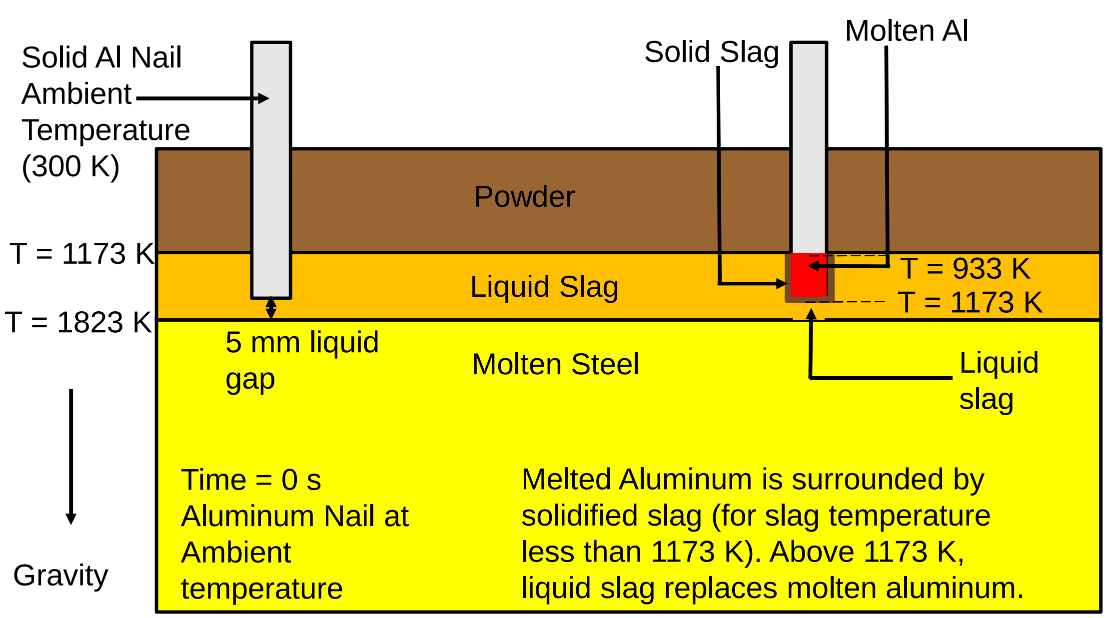
Solid Aluminum properties up to the melting temperature of Aluminum 933 K (660 °C). Molten Aluminum properties up to 1173 K (900 °C). Above 1173 K, slag properties.



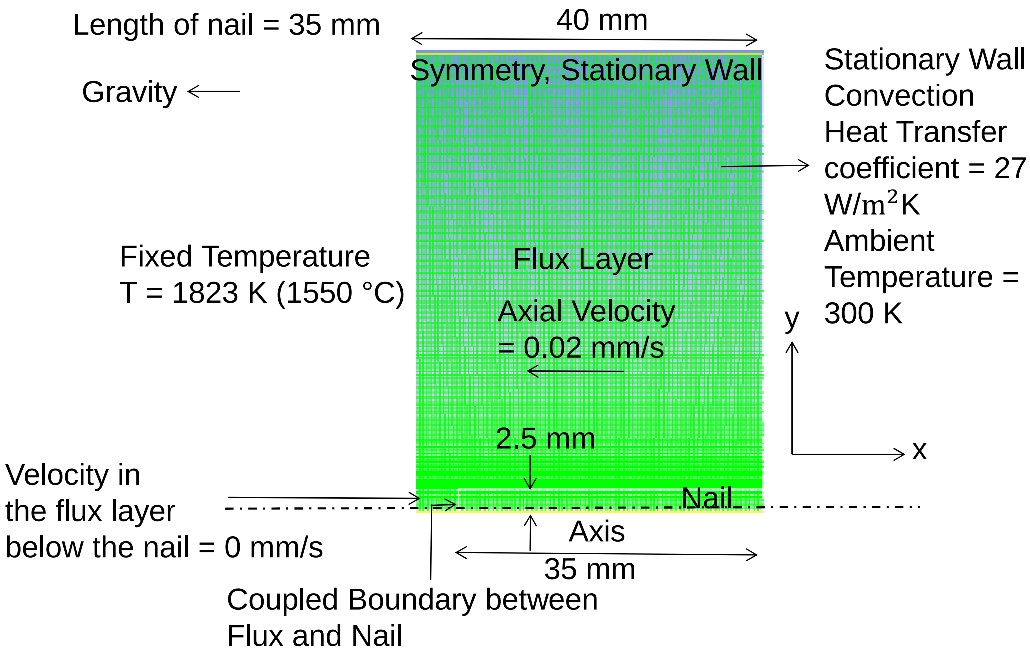


It can be seen that after approximately 6 s the length of the Aluminum nail predicts the actual liquid flux layer thickness.

Aluminum Nail Dipping Case 2



Mesh and boundary conditions (Nail length = 35 mm)



Minimum element length = 0.15 mm

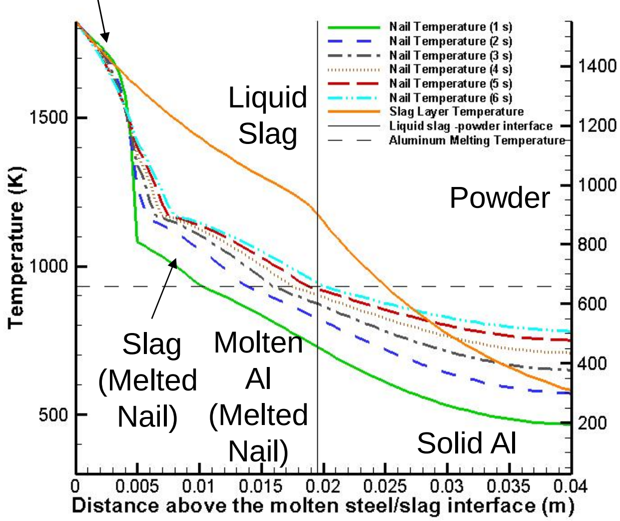
Aluminum Nail Surface Temperature variation with time (Case 2: Nail dipped 35 mm into flux)

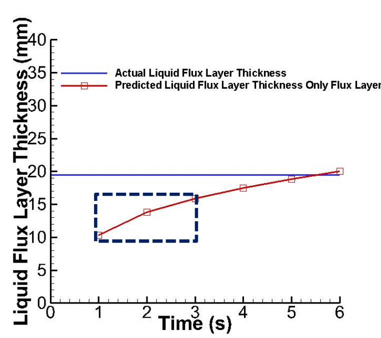
Liquid Slag below Nail

Solid Aluminum properties up to the melting temperature of Aluminum 933 K (660 °C). Molten Aluminum properties up to 1173 K (900 °C). Above 1173 K, slag properties.

Molten Steel

Gravity

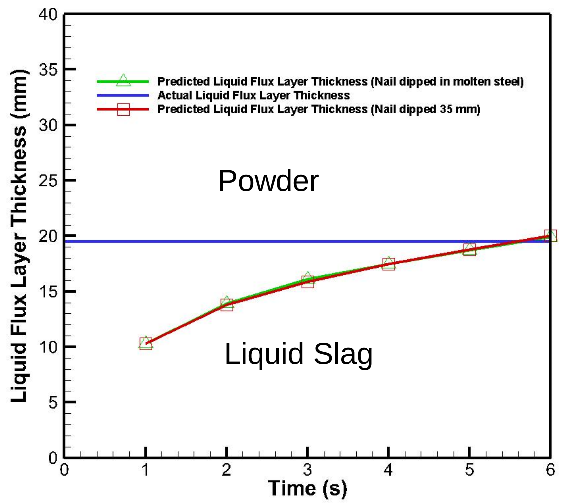




It can be seen that for the 35 mm dipped nail after approximately 6 s the length of the Aluminum nail predicts the actual liquid flux layer thickness.

Liquid Flux Layer Thickness prediction compare Case 1 and 2

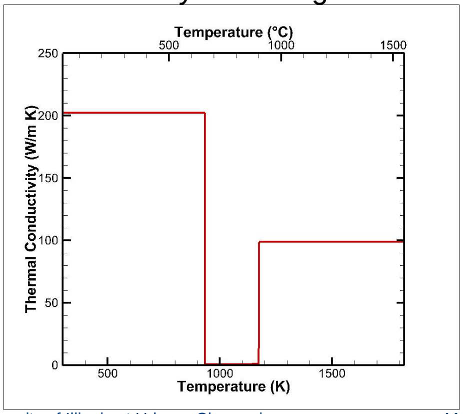
Gravity

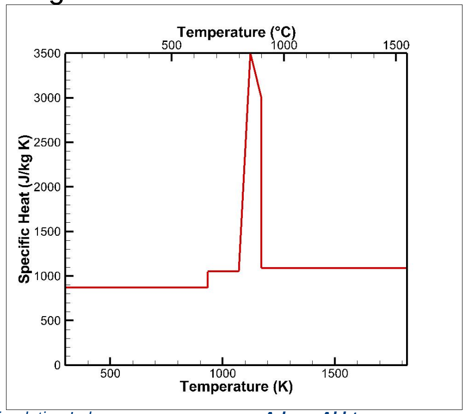


With both the nail dipped into the molten steel and the nail only in the flux layer, the time to reach the liquid flux layer thickness is the same – if the property scenario stays the same.

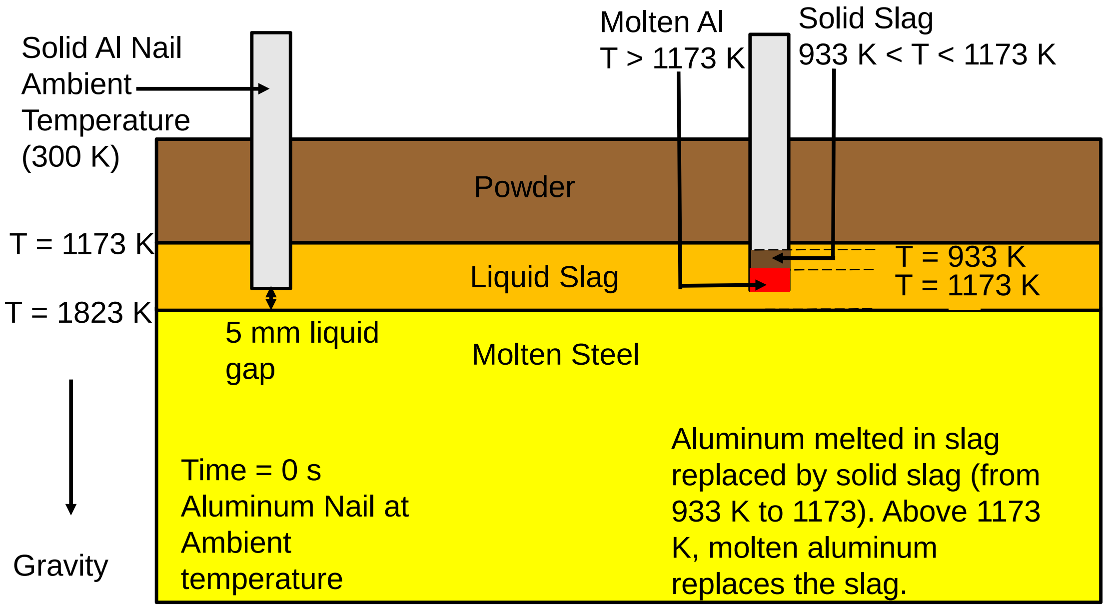
Properties defined in the nail region (Case 3)

1. The properties in the nail region in contact with the flux layer is defined by solid Aluminum properties up to the melting temperature of Aluminum 933 K (660 °C).
2. On melting the properties of slag are considered until the slag melting temperature of 1173 K (900 °C).
3. Above 1173 K, molten Aluminum properties are considered in the nail region.
4. Density in the region is constant = 2719 kg/m^3



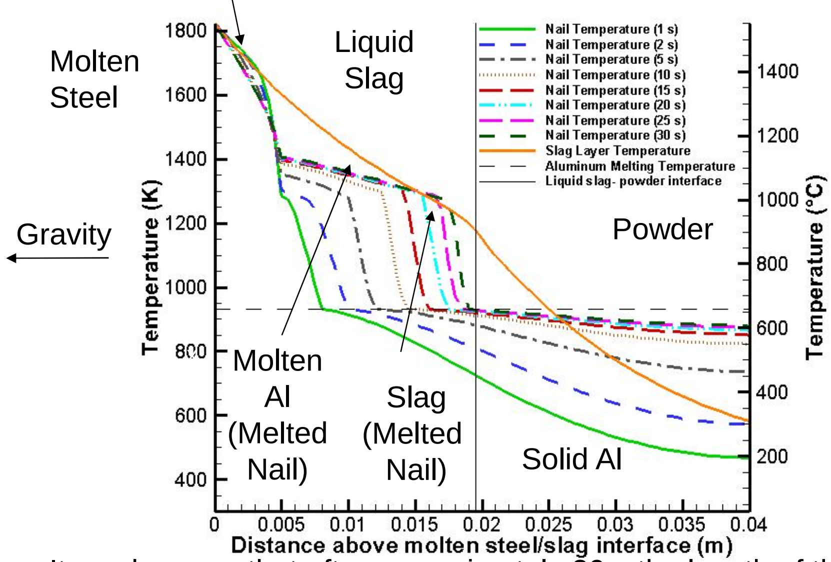


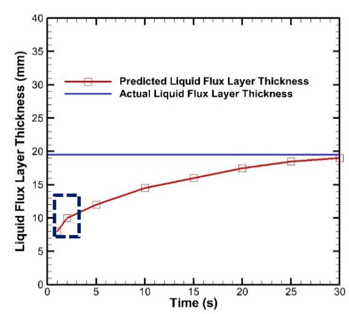
Aluminum Nail Dipping Case 3



Aluminum Nail Surface Temperature variation with time (Case 3 - Nail dipped 35 mm into flux)

Solid Aluminum properties up to the melting temperature of Aluminum 933 K (660 °C). Slag properties up to 1173 K (900 °C). Above 1173 K, molten Aluminum properties.





It can be seen that after approximately 30 s the length of the Aluminum nail predicts the actual liquid flux layer thickness.

Inferences from the heat transfer in a Aluminum nail

- The approximate time for nail dipping remains the same for a nail dipped in molten steel and only dipped in the flux layer (6 s). (Case 1 and 2)
- The time required to match the liquid flux layer thickness increases to 30 s. (Case 3)
- The drop in temperature is greater for the slag as compared to the molten aluminum due to the low thermal conductivity of the slag as compared to aluminum.
- Aluminum nail may be an accurate method to determine the liquid flux layer thickness, but might be unreliable.

Heat Transfer with slag consumption in the Flux Layer and Copper Nail

Copper Properties used in the simulation

- Copper Density= 8940 kg/m^3
- Copper Specific Heat = 390 J/kg K
- Copper Thermal Conductivity = 400 W/m K
- Molten Copper Specific Heat = 531.5 J/kg K
- Molten Copper Thermal Conductivity = 160 W/m K
- Melting Temperature of Copper = 1358 K

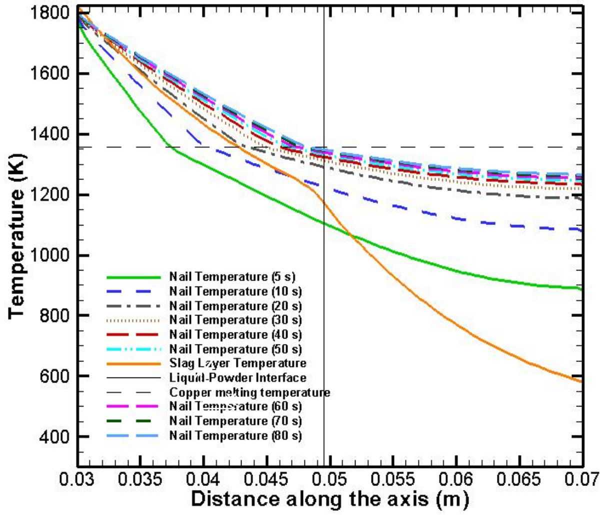
http://www.arc.vt.edu/ansys_help/flu_ug/flu_ug_biblio.html#XUGhsu-jemcov [13]
http://www.engineeringtoolbox.com/ [14]
Thermal conductivity measurement of molten copper using an electromagnetic levitator superimposed with a static magnetic field, Baba *et al*, Measurement Science and Technology 2012 [15]

Physical Significance of the properties in the nail region for a Copper nail

1. The Copper Nail remains solid until the temperature is lower than its melting temperature of 1358 K (1058 °C) .
2. As the Copper melts it forms molten copper. At this temperature, the slag is also in the liquid state.
3. As a result, at a temperature greater than 1358 K molten copper and liquid slag co-exist in the flux layer.
4. Two scenarios have been simulated for the copper nail:
   - Solid Copper at temperatures below 1358 K and liquid slag above 1358 K.
   - Solid Copper at temperatures below 1358 K and molten Copper above 1358 K.

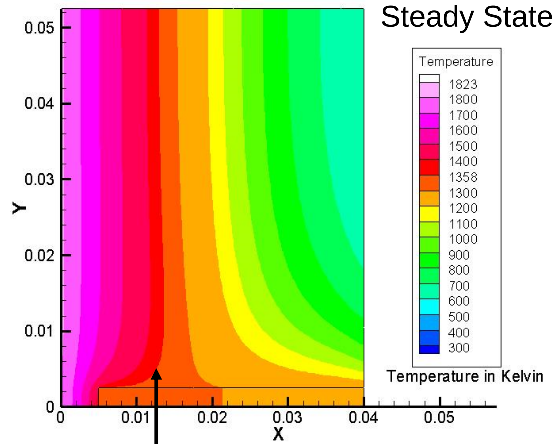
Copper Nail temperature variation with time

Melted Copper gap stays filled with molten copper



Copper nail dipped into flux layer with a 5 mm gap does not melt.

Steady State



Temperature =1358 K (Cu nail does not melt)

Actual Liquid Flux Layer thickness = 19.5 mm
Predicted Liquid flux layer thickness after 80 s = 18.2 mm
% Error = - 6.7 %

Conclusions (Copper Nail)

- Dipping a copper nail into the flux layer with a 5-mm gap above the molten steel: did not melt if the gap fills with liquid slag.
- Dipping a copper nail into the molten steel:
  - If the melted copper region stays filled with liquid copper, the nail eventually melts back to match the liquid slag layer thickness (7% error) after 80s.
  - If the melted copper is replaced with liquid slag, only 5-mm liquid-slag gap forms.
  - Thus, using copper nail is not reasonable (melting temp is too high).
  - Even using copper wire may not be reliable

Conclusions (Aluminum Nail)

- Dipping an Aluminum nail into the molten steel (Case 1)
  - If melted Al is initially a continuous column and later its bottom is replaced by slag, it takes 6 s to match the liquid flux layer thickness.
- Dipping an Aluminum nail into the flux layer (Case 2 & 3)
  - It still takes 6 s to match the liquid flux layer thickness (Similar to Case 1).
  - If the top of the column sinks beneath a solid slag barrier (Case 3), it takes 30 s to match the liquid flux layer thickness.
- Same amount of time to predict liquid flux layer thickness for a nail dipped in molten steel and flux only.
- In 3 seconds, the predicted value reaches within 20 % of the actual liquid flux layer thickness. (Case 1 and 2)
- Aluminum nail may be an accurate method to determine the liquid flux layer thickness, but might be unreliable.

Conclusions (Steel Nail) and Future Work

- For a steel nail, the average nail temperature was 340 °C at the location of the liquid flux layer thickness falls between dark grey and blue tempering colors of steel oxide (125 °C range).
- This suggests that the gray-blue tempering color on the steel nail can approximate the liquid-slag layer depth.
- Given the uncertainty of reading dark grey, it would be more accurate to measure from the dark purple discolored band (555 K) to the lump, and adjust according to:
  - Dipping time (90% at 1.5 s to 75% at 3 s)
- The flux consumption and total slag layer thickness do not significantly change this percentage.
- The aluminum nail dipped for 6s might give a better prediction, but depends on the melting / property scenario.

- **Future Work: Validate this methodology to predict liquid flux layer thickness with plant experiments.**

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)

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14) http://www.engineeringtoolbox.com/
15) Thermal conductivity measurement of molten copper using an electromagnetic levitator superimposed with a static magnetic field, Baba *et al*, Measurement Science and Technology 2012