CCC ANNUAL REPORT

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Modeling Heat Transfer in SEN during Preheating

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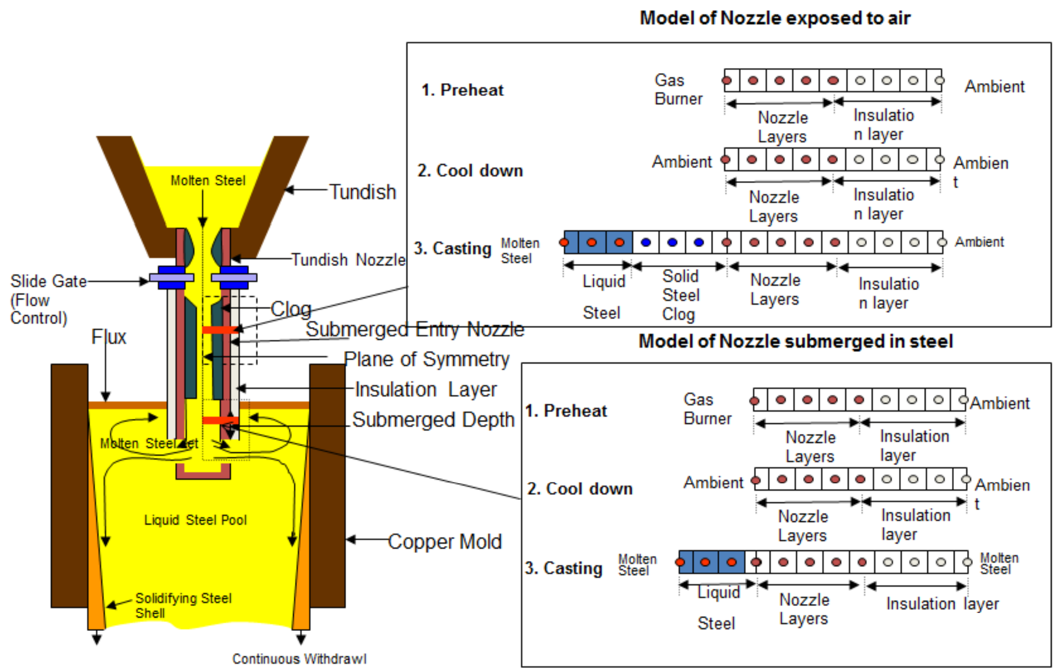
Objectives

1) Validate Singh VBA SEN heat-transfer model with analytical solution
2) Validate Singh VBA SEN model with measurements conducted during preheating
3) Improve and apply validated models to study SEN heat transfer during preheating, cool-down, and casting

Singh VBA Spreadsheet Model of SEN



Singh's SEN Model - Main page

Geometry of Nozzle					
Outer Radius of Refractory	78	mm			
Enter Number of layers	3				
Emmissivity	0.1				
Preheat					
Ambient Temperature	19.0	°C			
Initial Nozzle Temperature	9.0	°C			
FlameTemperature	1262.0	°C			
Internal heat transfer Coefficient (forced)	20.0	W/(m²K)			
External heat transfer Coefficient (free)	10	W/(m²K)			
Preheat Time	120.0	min.			
Time Step	0.01	s			
Time interval between printing	0.5	min.			
Times to plot from start of preheat (min.)	1	3	10	30	120
Points to plot temperature, Distance from outer surface (mm)	0	10.76	32.16	40.7	41.4
Cooldown					
Ambient Temperature (Outside)	19.0	°C			
Ambient Temperature (Inside)	19.0	°C			
Internal heat transfer Coefficient	10.00	W/(m²K)			
External heat transfer Coefficient	10	W/(m²K)			
Cooldown Time	15.0	min.			
Time Step	0.01	s			
Time interval between printing	0.5	min.			
Times to plot from start of cooldown (min.)	1	2	5	10	15
Points to plot temperature, Distance from outer surface (mm)	0	10.76	32.16	40.7	41.4
Casting					
Pour Temperature	1550.0	°C			
Solidification Temperature	1525.0	°C			
Ambient Temperature (Outside)	19.0	°C			
Internal heat transfer Coefficient	33594.11	W/(m²K)			
External heat transfer Coefficient (free)	10.0	W/(m²K)			
Casting Time	5.0	min.			
Time Step	0.01	s			
Time Interval between printing	0.02	min.			
Steel Layer thickness	10.0	mm			
Steel Layer mesh size	0.5	mm			
Times to plot from start of casting (min.)	0.5	1	1.5	2	5

Clear

Assign Refractory Properties

Preheat Simulation

View Preheat Plots

Cooldown Simulation

View Cooldown Plots

Assign Steel Properties

Casting Simulation

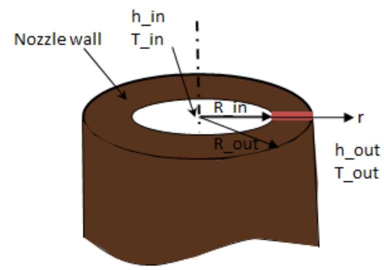
View Casting Plots

Governing equation & boundary conditions for test problem

Governing Heat Transfer Equation

$$\rho C_p \frac{\partial T}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)$$

3-D Schematic of SEN



Boundary conditions

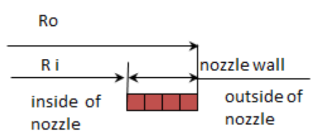
$$-k\left.\frac{\partial T}{\partial r}\right|_{inner\ surface} = q'' = h_{in}(T_{in} - T_{insurface})$$

$$-k\left.\frac{\partial T}{\partial r}\right|_{outurface} = q'' = h_{out}(T_{outsurface} - T_{out})$$

Test problem in Singh model

In the nozzle wall there is only one layer with test material.

1-D Schematic of Singh VBA model



Discretized heat transfer equations for Singh model

Interior nodes

$$T_i^{n+1} = T_i^n + \alpha\Delta t[T_{i+1}^n\left(\frac{1}{\Delta r^2} + \frac{1}{2r\Delta r}\right) + T_{i-1}^n\left(\frac{1}{\Delta r^2} - \frac{1}{2r\Delta r}\right) - \frac{2T_i^n}{\Delta r^2}]$$

Boundary nodes

$$T_i^{n+1} = T_i^n + \frac{2\alpha\Delta t}{r\Delta r}[\left(r + \frac{\Delta r}{2}\right)\left(\frac{T_i^n - T_{i+1}^n}{\Delta r}\right) + \frac{2\Delta t h r}{\rho C_p r\Delta r}(T_{ambient} - T_i^n)]$$

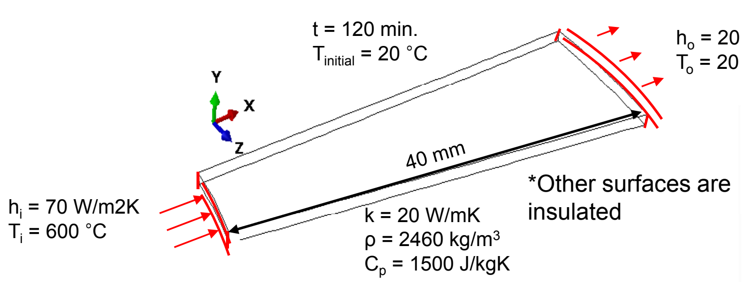
Interface nodes

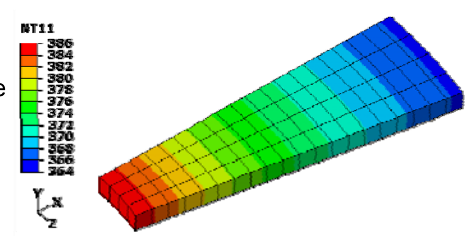
$$T_i^{n+1} = T_i^n + \frac{\Delta t}{r\frac{\Delta r_2 + \Delta r_1}{2}}[\frac{\alpha_2\left(r + \frac{\Delta r_2}{2}\right)}{\Delta r_2}(T_{i+1}^n - T_i^n) - \frac{\alpha_1\left(r + \frac{\Delta r_1}{2}\right)}{\Delta r_1}(T_i^n - T_{i-1}^n)]$$

Test problem conditions

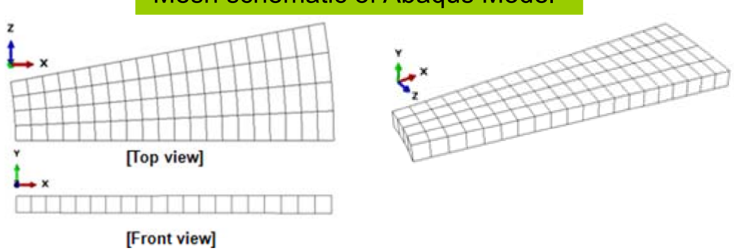
Test conditions	Input value
Inside temperature	600 ℃
Outside temperature	20 ℃
Inside heat transfer coefficient	70 W/m^{2}K
Outside heat transfer coefficient	20 W/m^{2}K
Inside radius	40 mm
Outside radius	80 mm
Heat conductivity	20 W/m K
Density	2460 kg/m^3
Specific heat	1500 J/kg K

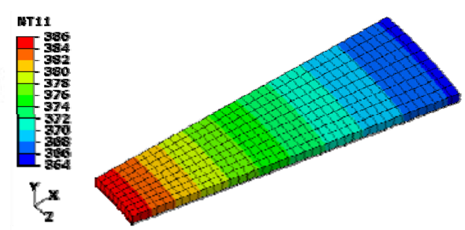
Test Problem in Abaqus





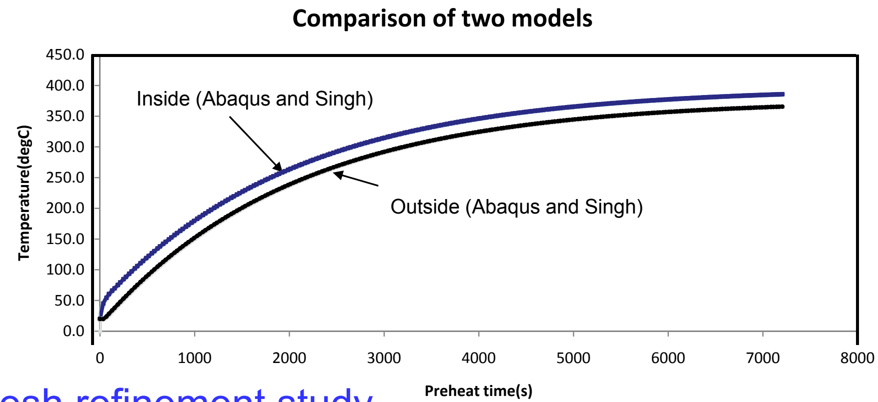
Mesh schematic of Abaqus Model*





* form Hyoung-Jun Lee, Test_Abaqus model_Hyoung-jun Lee, 2011, 07

Comparison of Abaqus and Singh-model



Mesh refinement study

Singh's number of nodes	Abaqus inside*	Singh inside*	Error of inside	Abaqus outside*	Singh outside*	Error of outside
5	385.7°C	385.8°C	0.1°C	365.5°C	365.7°C	0.2°C
9	385.7°C	385.7°C	0	365.5°C	365.5°C	0
21	385.7°C	385.7°C	0	365.5°C	365.5°C	0

5 nodes is accurate enough

*temperature at 120mins at SEN surface

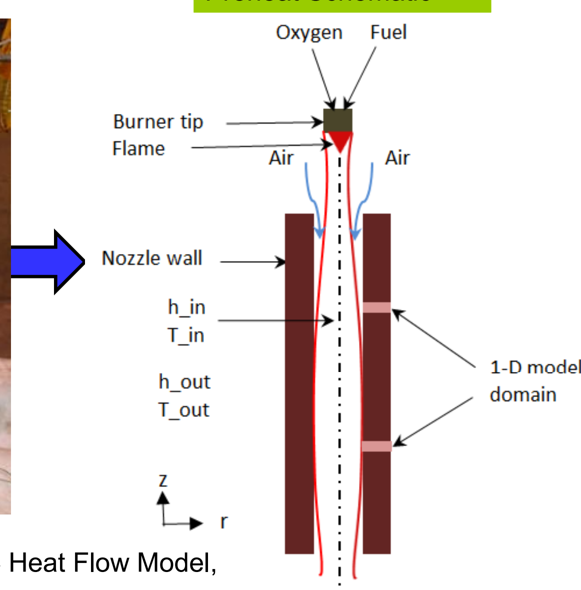
SEN Preheating

• Preheating is by fuel and oxygen combustion; product gas mixed with entrained air flows into SEN, which increases nozzle wall temperature.

Thermocouples are installed at the hottest region of the SEN body.

Preheat Set-up*

Preheat Schematic

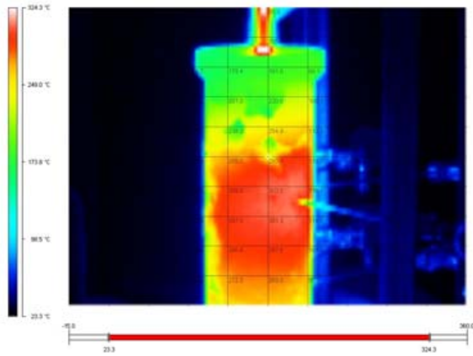


* from PB10 SEN Temperature Data for CCC Heat Flow Model, Magnesita Refractories Research report

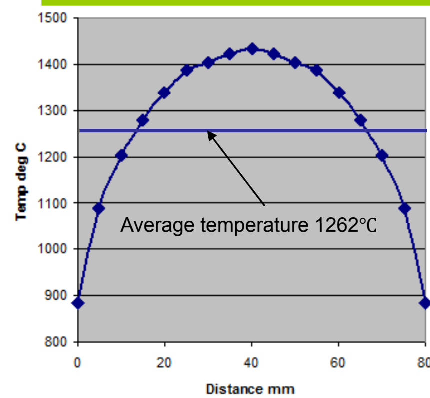
Preheating Experiment

• The preheating mechanism is the fuel and oxygen combustion, then the product gas mixed with air flows into SEN, which make SEN temperature increased.

Infra-red image of SEN*



Gas temperature across SEN*

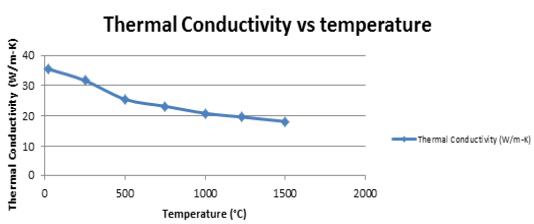


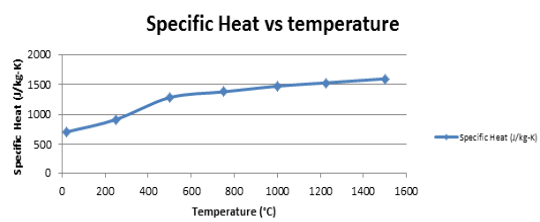
Based on the gas composition and no air dilution, the flame temperature was calculated as 3100℃. The gas temperature across the SEN shows the actual flame temperature was probably only realized at the burner tip.*

* from PB10 SEN Temperature Data for CCC Heat Flow Model, Magnesita Refractories Research report

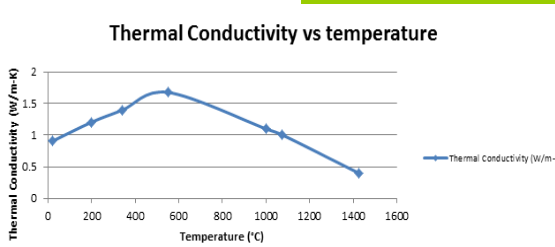
Refractory Temperature Dependent Properties*

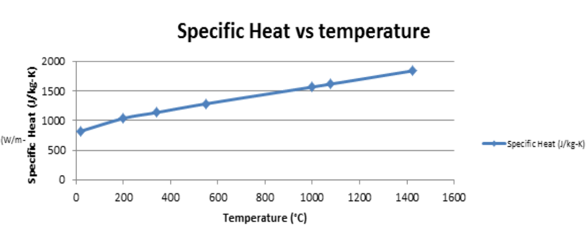
Material Alumina Thermo-properties





Glaze Material Thermo-properties





* from Rob Nunnington, Magnesita Refractories

Sensitivity Study - Introduction

Approach of Sensitivity Analysis

❖Choose standard conditions of all variables to get standard result
❖For each variable, choose a reasonable engineering estimate of its most extreme value
❖For each variable, calculate a new result using its new value while keeping the same constant standard conditions for all of the others
❖Compare the new results with the standard result

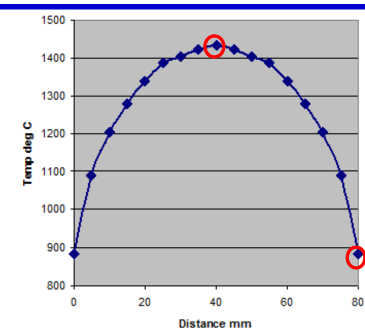
Why need Sensitivity analysis?

*** To determine which variables are most important**

Sensitivity Study of Steady state Model

What value of these three variables in Singh VBA Model are need to match measurement result?

Estimated uncertainty of gas temperature:
Highest temperature-lowest temperature
=1432-885=547℃



Independent variable	Standard	Estimated uncertainty	New result	Standard(372℃) Error
Gas Temperature	600℃	+547℃	704℃	+332℃
External Temperature	20℃	-10℃	368℃	-4℃
Internal convection coefficient	70W/m2K	-10 W/m²K	352℃	-20℃
External convection coefficient	20 W/m2K	-10 W/m²K	457℃	+86℃
Heat conductivity	20W/mK	-5 W/mK	369℃	-3℃

The most important variables

Big error!

Flame Temperature Model—Main Page

Main Page *

Set GASEQ executable file path:	Browse...	C:\Program Files (x86)\GASEQ\Gaseq.exe
Select Fuel :	Methane	
Select Oxygen Source for combustion gas	Oxygen	
Oxygen Enrichment relative to stoichiometric (%)	0	
Air Entrainment relative to stoichiometric (%)	165.8	
	Reactants	Products
Temperature (°C)	19	1262.1
Pressure (atm)	1	1

Species	Reactants (%)	Reactants (moles)	Products (moles)	Products (%)
Methane (CH_4)	5.3	1.00E+00	0.00E+00	0.0
Oxygen (O_2)	28.3	5.32E+00	3.30E+00	17.6
Nitrogen (N_2)	66.4	1.25E+01	1.25E+01	66.3
Carbon dioxide (CO_2)	0.0	0.00E+00	1.00E+00	5.3
Carbon monoxide (CO)	0.0	0.00E+00	1.92E-05	0.0
Hydrogen (H_2)	0.0	0.00E+00	1.41E-05	0.0
Water (H_2O)	0.0	0.00E+00	2.00E+00	10.6
Hydroxide (OH)	0.0	0.00E+00	2.00E-03	0.0
Hydrogen atom (H)	0.0	0.00E+00	4.31E-07	0.0
Oxygen atom (O)	0.0	0.00E+00	5.04E-05	0.0
Nitric Oxide (NO)	0.0	0.00E+00	2.47E-02	0.1

Calculate | Reset | Help

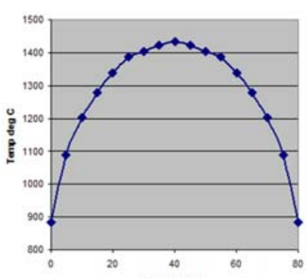
* form Flame Temperature Model, Varun K. Singh, 2010

Use Flame Temperature Model to calculate product temperature

The Stoichiometric reaction for methane is :

$$CH_4 + 2O_2 + 2*79/21\ N_2 = CO_2 + H_2O + 2*79/21\ N_2$$

Select Fuel :	Methane	
Select Oxygen Source for combustion gas	Oxygen	
Oxygen Enrichment relative to stoichiometric (%)	0	
Air Entrainment relative to stoichiometric (%)	0	
	Reactants	Products
Temperature (°C)	19	2780.3
Pressure (atm)	1	1



Average products Temperature is 1262℃。

Adjust Air Entrainment to match 1262℃

Select Oxygen Source for combustion gas	Oxygen	
Oxygen Enrichment relative to stoichiometric (%)	0	
Air Entrainment relative to stoichiometric (%)	165.8	
	Reactants	Products
Temperature (°C)	19	1262.1
Pressure (atm)	1	1

Use Flame Temperature Model to calculate convection coefficient

It should notice that not all the product gas flow into the SEN. Most part of the gas flow from the outside SEN. In a reasonable domain, I assume 2% gas flow into the SEN to get the reasonable flow rate and gas velocity inside the SEN.

Heat Transfer Coefficient Calculation Model*

Forced Convection (flame on the inside) and Free Convection (ambient on the outside)

Flame Temperature	1262	°C
Outside Surface Temperature	450	°C
Nozzle Orifice Area	6.54E+00	$inch^2$
Characteristic diameter	0.0732	m
Gas Pressure	9	PSI
Friction Factor	0.03	m/m
Gas Pressure	6.21E+04	Pa
Nozzle Orifice Area	4.22E-03	m^2
Gas Density	1.87E-01	kg/m^3
Velocity	1.63E+01	m/s
Mass flow Rate	1.28E-02	kg/s
Free Convection	7.55	W/m^2-K
Forced Convection	21.11	W/m^2-K

Calculate

Put these two coefficients into Singh Heat Transfer Model

Are all these input will make Singh Heat Transfer Model 's predict temperature match with measurement?

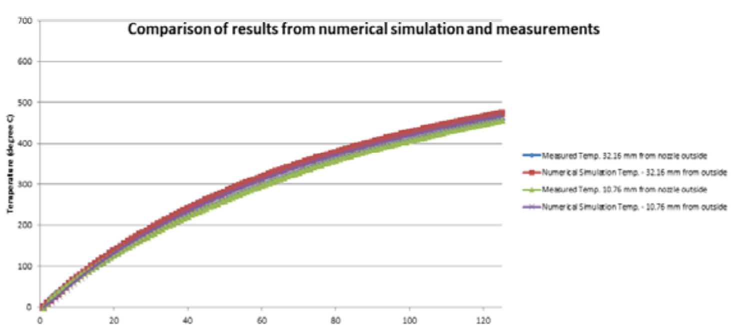
*form Flame Temperature Model, Varun K. Singh, 2010

Results of Singh VBA Model Comparison with Measurements

Input of Singh Heat Transfer Model

Geometry of Nozzle		
Outer Radius of Refractory	78	mm
Enter Number of layers	3	
Emmissivity	0.1	

Preheat		
Ambient Temperature	19.0	°C
Initial Nozzle Temperature	9.0	°C
FlameTemperature	1262.0	°C
Internal heat transfer Coefficient (forced)	21.0	$W/(m^2K)$
External heat transfer Coefficient (free)	7.55	$W/(m^2K)$
Preheat Time	120.0	min.
Time Step	0.01	s
Time interval between printing	0.5	min.
Times to plot from start of preheat (min.)	1	3
Points to plot temperature, Distance from outer surface (mm)	0	10.76



Other possible matched cases

In all four cases, Singh VBA SEN heat-transfer model matched with measurement data very well.
More work is needed to find the most realistic case.

	Gas Temperature(℃)	Internal forced convection coefficient(W/m²K)	External forced convection coefficient(W/m²K)
Case 1	750	47	7
Case 2	900	33	5
Case 3	1000	30	9
Case 4	1262	21	8

Conclusion

- Through Abaqus Test problem, Singh's VBA heat transfer Model works well at one layer with constant material properties.
- Through Sensitivity Analysis, gas product temperature, internal and external convection heat transfer coefficient are the three most important variables affect heat transfer across SEN. Based on sensitivity analysis, we find the major variables to match Singh heat transfer Model with measurement.
- By using Flame Temperature Model, users can predict internal and external heat transfer coefficient. Predicted by this model, 21W/m²K for internal and 7.55 W/m²K for external work very well to match with measurement temperature.

Acknowledgement

- Continuous Casting Consortium

  (LWB Refractories ,ABB, Arcelor-Mittal, Baosteel, Corus, Nucor Steel, Nippon Steel, Postech, Posco, ANSYS-Fluent.)
- Rob Nunnington, LWB Refractories
- Graduate students:

  - Hyoung-Jun Lee