ANNUAL REPORT 2012

UIUC, August 16, 2012

Modeling Heat Transfer in SEN during Preheating & Cool-down

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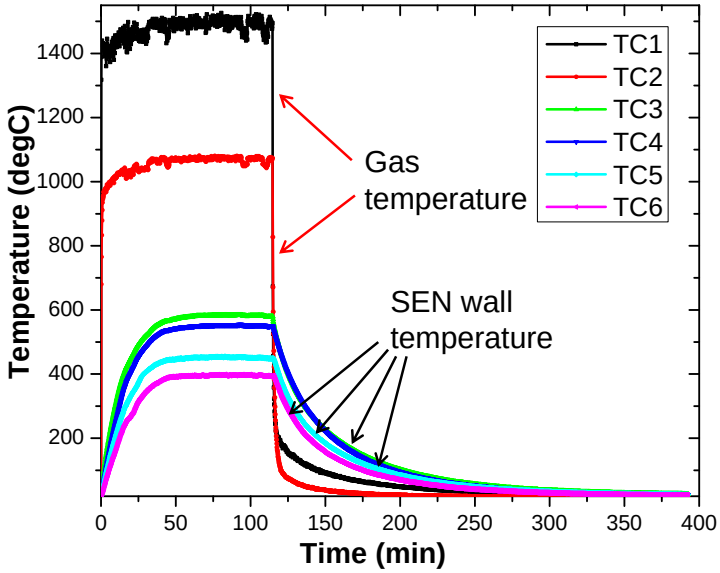
Project Background
(long term goals)

- SEN Preheating ⇨ Prevent thermal shock cracks
- Cool down process ⇨ Transport the preheated SEN
- Initial Casting Immersion ⇨ Possible skulling in mold and associated defects
- 3D commercial software model
  ⇨ Long time& expansive
  ⇨ 1D User friendly Visual Basic Application

Background: Torch preheating experiment for model validation

Set-up[1]

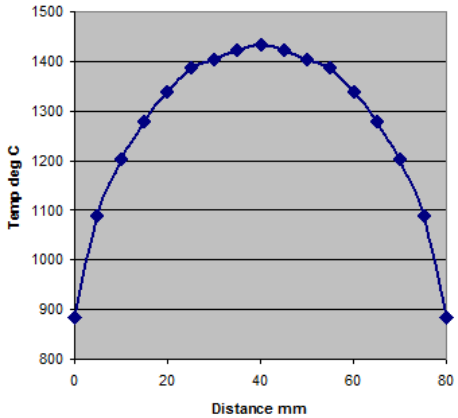
Thermal Couple temperature histories (Run2)



Background: Torch preheating experiment for model validation

Infra-red thermal image

Flame profile across SEN bore

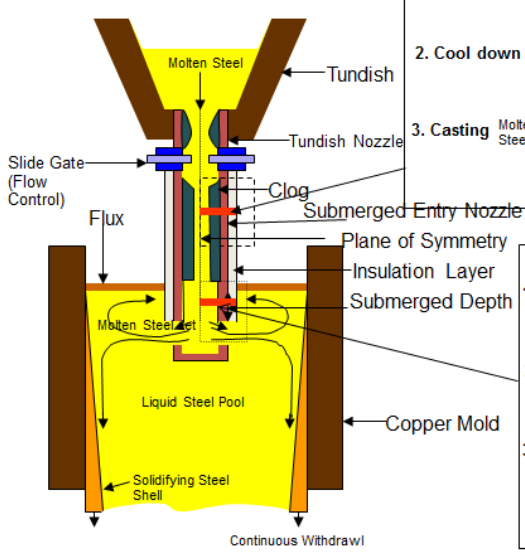


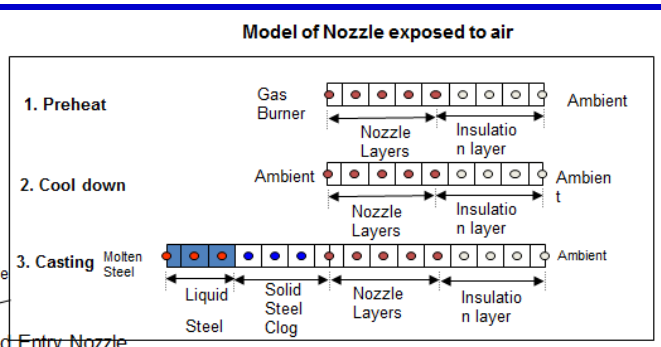
Model Approach

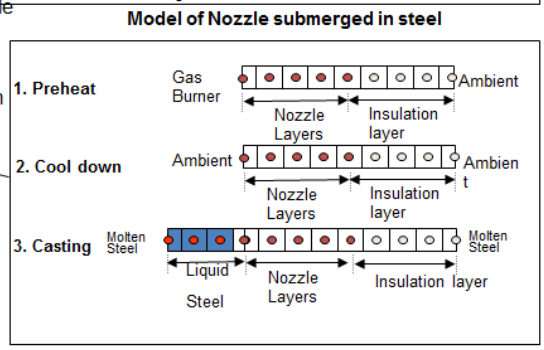
- Combustion, Fluid flow, and Heat Transfer in and near Nozzle with 2-D axisymmetric FLUENT model
- Post processing to get heat transfer coefficients
- Heat conduction in nozzle wall with 3-D FLUENT model for validation of VBA model
- VBA model of heat transfer in nozzle wall (simple Excel spread-sheet model)

Background: VBA Model Scheme

VBA Spreadsheet Heat Transfer Model of SEN







VBA Model[2]* Main Page

Heat Transfer Model of skull clogging for variable layers

Geometry of Nozzle					
Outer Radius of Refractory	75.79	mm			
Enter Number of layers	3				
Emmissivity	0.82				
Preheat					
Ambient Temperature	19.0	°C			
Initial Nozzle Temperature	19.0	°C			
SEN inner wall Temperature	885.0	°C			
Internal heat transfer Coefficient(TC1 location)	50.9	W/(m^{2}K)			
External heat transfer Coefficient	35.25	W/(m^{2}K)			
Preheat Time	115.0	min.			
Time Step	0.00	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)	20.0	°C			
Ambient Temperature (Inside)	436.0	°C			
Internal heat transfer Coefficient	20.00	W/(m^{2}K)			
External heat transfer Coefficient	20	W/(m^{2}K)			
Cooldown Time	277.7	min.			
Time Step	0.00	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/(m^{2}K)			
External heat transfer Coefficient (free)	35.3	W/(m^{2}K)			
Casting Time	5.0	min.			
Time Step	0.00	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

* From Varun K. Singh, User-friendly model of heat transfer in submerged entry nozzle during preheating, cool down and casting

Current Objectives

Combustion Model

- Use ANSYS software package to simulate natural gas and oxygen combustion in the preheating process.
- Obtain the temperature distribution of the SEN and heat transfer coefficients.
- Obtain entrained mass flow rate of air which also participate in the combustion.

VBA Model

- Validate 1D VBA heat transfer Model with 3D same conditions FLUENT Model.
- Use 1D VBA Model to match with experiment.

Combustion Model Assumption

- The combustion is a 2D axisymmetric process.
- The geometry of the SEN is simplified, and port is axisymmetric.
- One central equal area hole has the same effect on flame distribution.
- Natural gas is modeled as Methane (94% gas composition is methane).
- Gas completely mixed before exit from rosebud.

Assumption of Rosebud and Velocity

Multiport Rosebud simplification

There are 24 diameter about 1.6mm holes and 1 0.8mm diameter center hole on the Rosebud. The total area of the 25 holes is 5.027e-5 $m^{2.}$.

All Runs*	Flow rate (CFM)	Flow rate (m^3/s)	Pressure (PSI)	Pressure (Pa)
Oxygen	6	2.832e-3	45	3.103e5
Gas(CH4)	7.5	3.540e-3	9	6.206e4

Ideal gas law $\mathbf{P\dot{V} = n\dot{R}T}$

$$\dot{V}_{total} = \frac{P_{O2}\dot{V}_{O2} + P_{CH4}\dot{V}_{CH4}}{P_{atm}} = 17.12e-3\ m3/s$$

The molar rate ratio of CH4 and O2

$$\frac{\dot{n}_{CH4}}{\dot{n}_{O2}} = \frac{P_{CH4}}{P_{O2}} \cdot \frac{\dot{V}_{CH4}}{\dot{V}_{O2}} \cdot \frac{T_{O2}}{T_{CH4}} = \frac{33.16\%}{66.84\%}$$

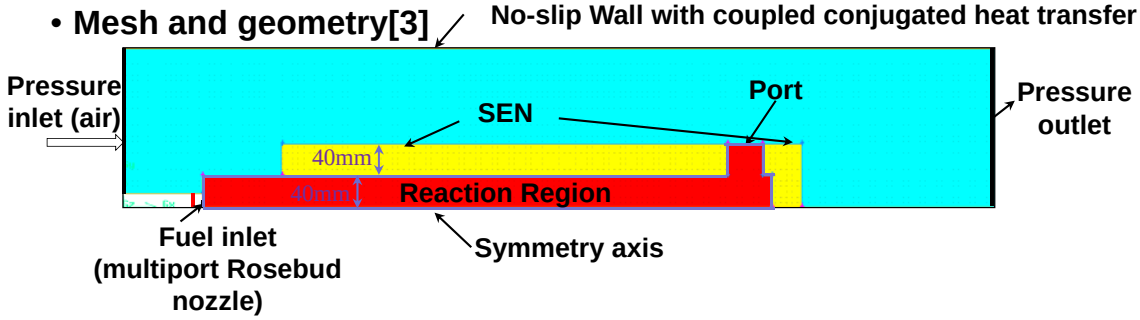
$$V_{velocity} = \frac{\dot{V}_{total}}{Area} = 342.60\ m/s$$

Artificially decreased flow rate to avoid supersonic instability.

Gas velocity at the Rosebud is 30m/s.

Mesh and Geometry

- **Mesh and geometry[3]**



- 2-D axisymmetric cylindrical combustor
- 219,624 nodes, 652,151 quadrilateral cells

Fuel Inlet	30m/s, 800K, CH4 33.16%, O2 66.84%
	Velocity inlet boundary condition Flow is turbulence

Combustion Model Settings[4]

Model	Steady state, 2D Axisymmetric
	Energy conservation
	Standard k-epsilon, Standard Wall Function
	Species transport volumetric model (inlet diffusion, diffusion energy source, thermal diffusion, finite-rate/eddy dissipation)
Material	Mixture (eg: CH4, O2, CO2, H2O, N2)
	Density: incompressible ideal gas
	Specific heat: mixing law
	Thermal conductivity0.0454 W/m K, Viscosity1.72e-5 kg/m s
	Mass diffusivity: kinetic theory
Solver	Pressure based solver
Pressure Schemes	SIMPLE, 2nd order upwind
Momentum, Energy, Species Discretization	1st order upwind

Combustion Model Governing Equation

2D Axisymmetric Continuity Equation[5] (Liquid flow)

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial r}(\rho v_r) + \frac{\rho v_r}{r} = S_m$$

2D Axisymmetric Momentum Equation (Liquid flow)

$$\frac{\partial}{\partial t}(\rho v_x) + \frac{1}{r}\frac{\partial}{\partial x}(r\rho v_x v_x) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r v_x) = -\frac{\partial P}{\partial x} + \frac{1}{r}\frac{\partial}{\partial x}[r\mu(2\frac{\partial v_x}{\partial x} - \frac{2}{3}(\nabla\cdot\vec{v}))] + \frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(\frac{\partial v_x}{\partial r} + \frac{\partial v_r}{\partial x}\right)\right] + F_x$$

$$\frac{\partial}{\partial t}(\rho v_r) + \frac{1}{r}\frac{\partial}{\partial x}(r\rho v_x v_r) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r v_r) = -\frac{\partial P}{\partial r} + \frac{1}{r}\frac{\partial}{\partial r}[r\mu(2\frac{\partial v_r}{\partial r} - \frac{2}{3}(\nabla\cdot\vec{v}))] + \frac{1}{r}\frac{\partial}{\partial x}\left[r\mu\left(\frac{\partial v_r}{\partial x} + \frac{\partial v_x}{\partial r}\right)\right] + F_r$$
$$-2\mu\frac{v_r}{r^2} + \frac{2}{3}\frac{\mu}{r}(\nabla\cdot\vec{v})$$

Energy Equation

$$\frac{\partial}{\partial t}(\rho E) + \nabla\cdot\left(\vec{v}(\rho E + p)\right) = \nabla\cdot(k_{eff}\nabla T - \sum_j h_j\vec{J_j} + (\overrightarrow{\bar{\tau}_{eff}}\vec{v})) + S_h$$

Species Transport equations (eg. 5 for CH4, O2, N2, CO2, H2O)

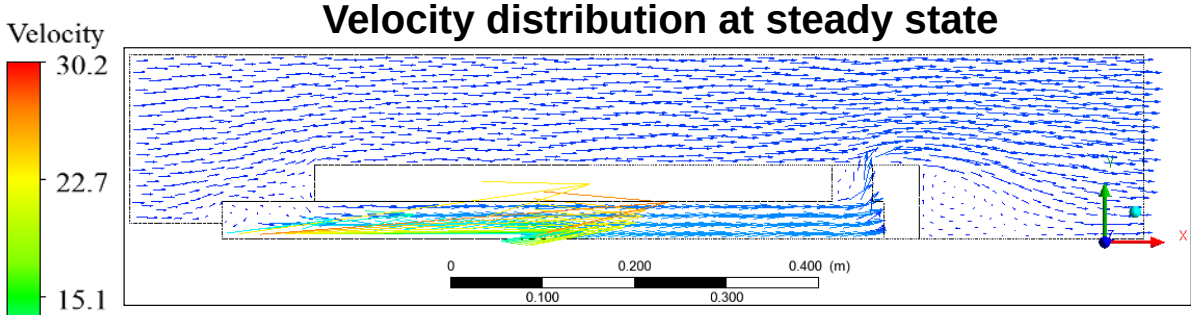
$$\frac{\partial}{\partial x}(\rho Y_i) + \nabla\cdot(\rho\vec{v}Y_i) = -\nabla\cdot\vec{J_i} + R_i + S_i$$

The Eddy-Dissipation Model

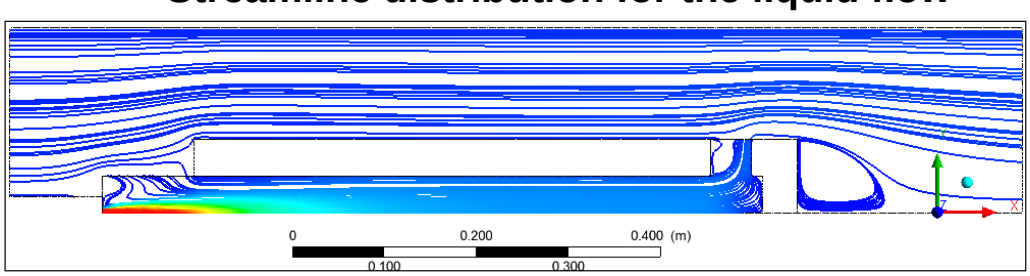
$$R_{i,r} = v'_{i,r}M_{w,i}AB\rho\frac{\varepsilon}{k}\frac{\sum PY_p}{\sum_j^N M_{w,j}v''_{j,r}}$$

Fluid flow Model Results[6]

Velocity distribution at steady state

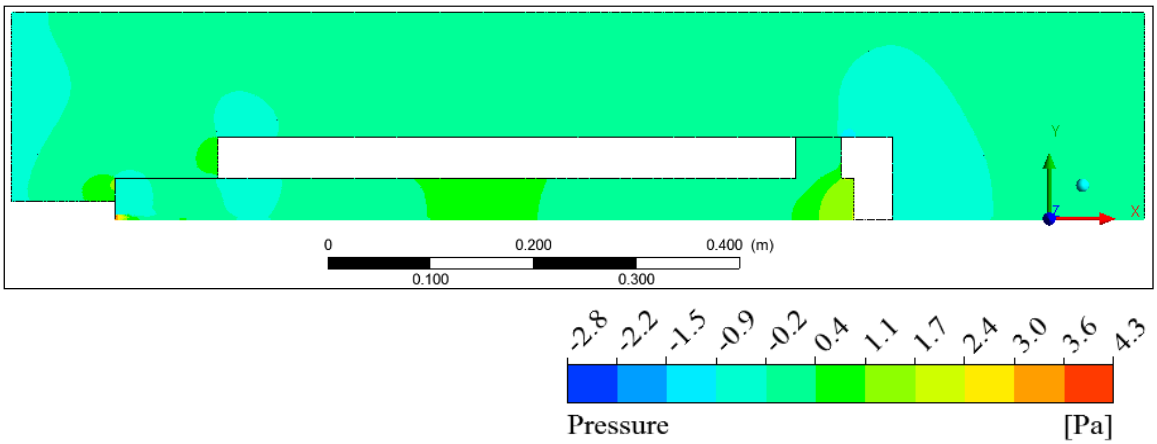


Streamline distribution for the liquid flow



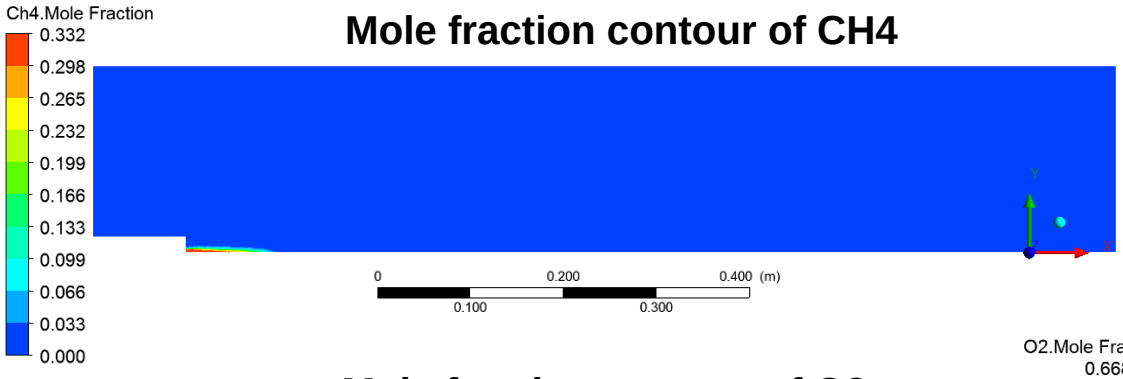
Pressure distribution

Pressure field

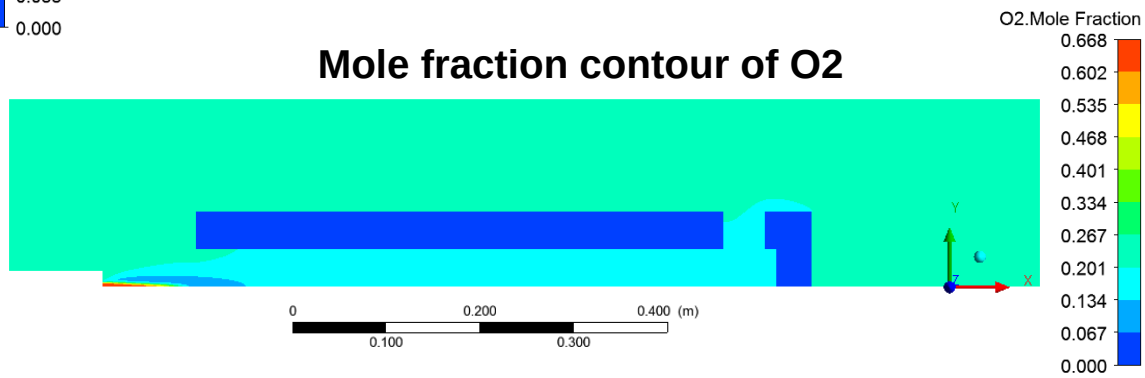


Species Results: CH4

Mole fraction contour of CH4

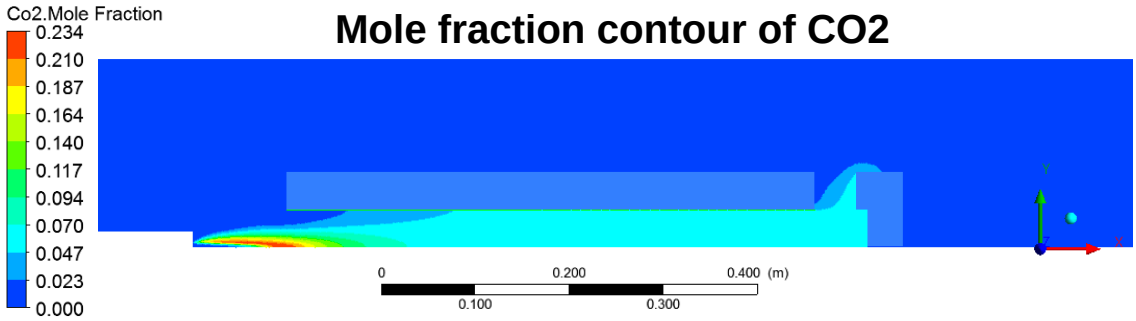


Mole fraction contour of O2

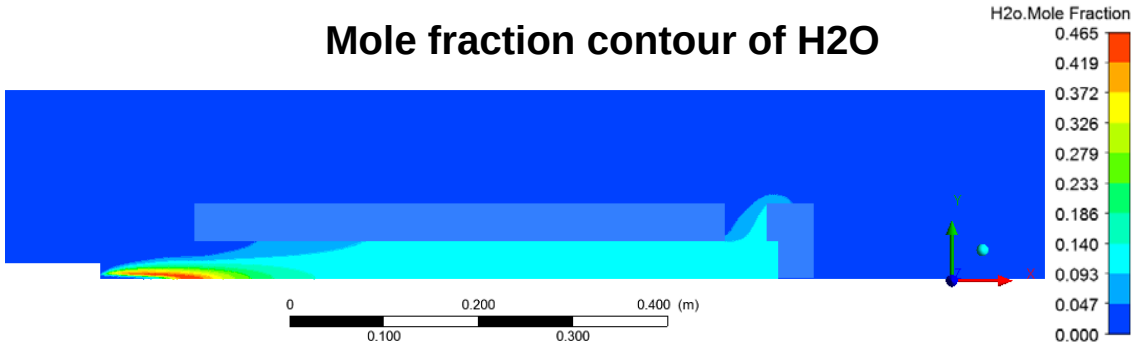


Species Results: H2O, CO2

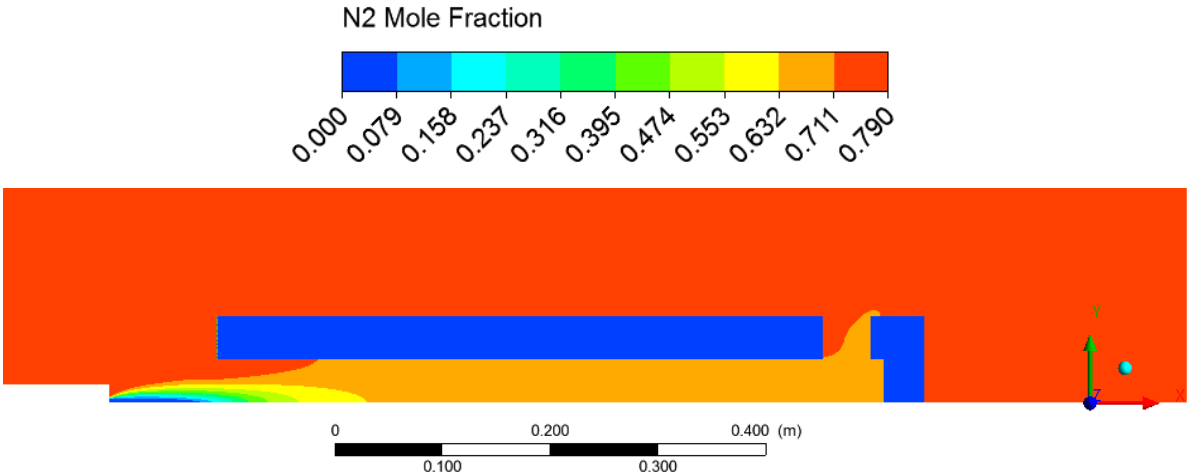
Mole fraction contour of CO2



Mole fraction contour of H2O



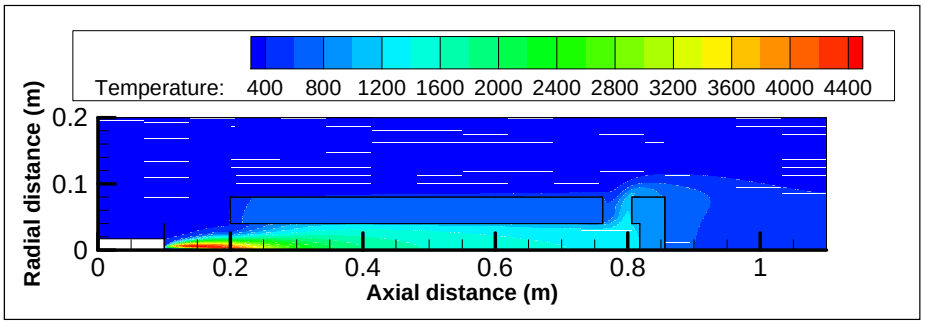
Species of N2



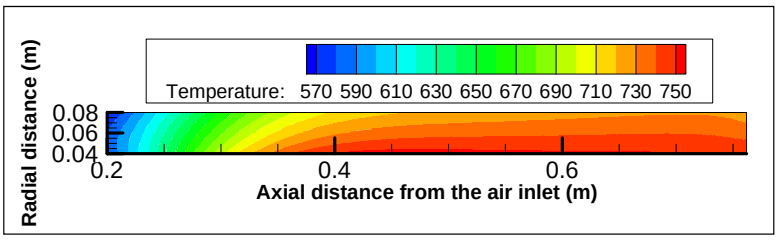
Mole fraction contour of N2

Combustion Model whole domain temperature contour[4]

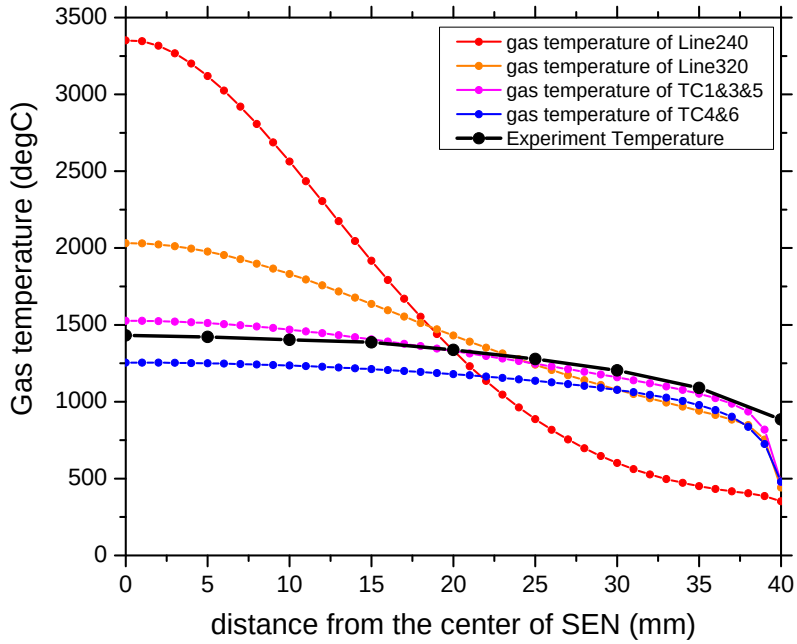
Temperature distribution of whole domain



Temperature distribution of the upper SEN

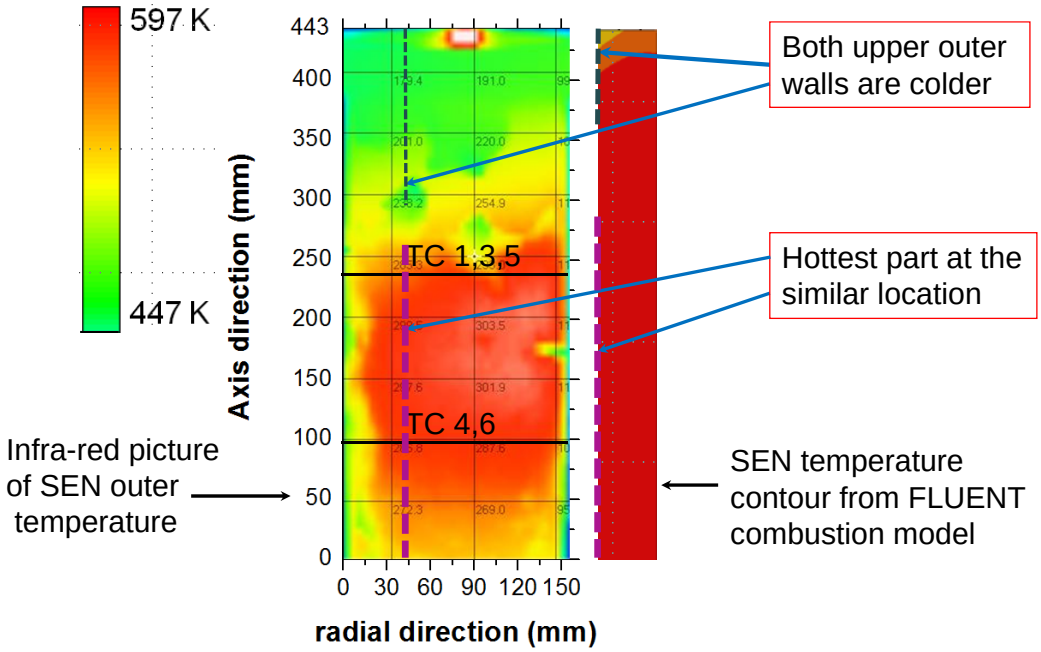


Gas temperature at different axial location of inner SEN



Temperature in Nozzle Outer Wall

Surface temperature



Heat transfer coefficient and Entrained air mass flow rate

Location		Surface heat transfer coefficient
TC1 axial level*	Inner SEN wall	50.89 W/Km^2
	Outer SEN wall	35.25 W/Km^2
TC4 axial level*	Inner SEN wall	34.43 W/Km^2
	Outer SEN wall	27.58 W/Km^2

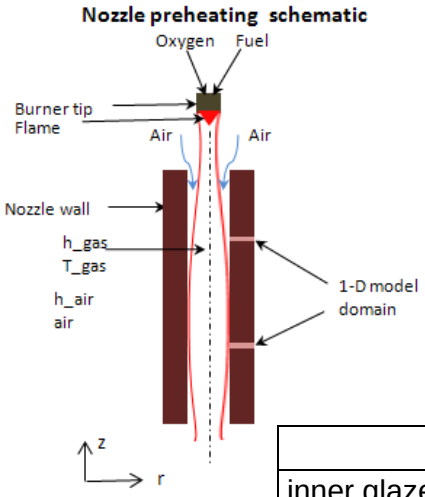
Line surface across the SEN	Mass flow rate (Kg/s)
Mixture exit	6.135e-4
SEN inlet	39.590e-4
Net mass flow rate**	33.455e-4

Air entrainment relative to stoichiometric is 5.11% to input in Flame temperature VBA Model.

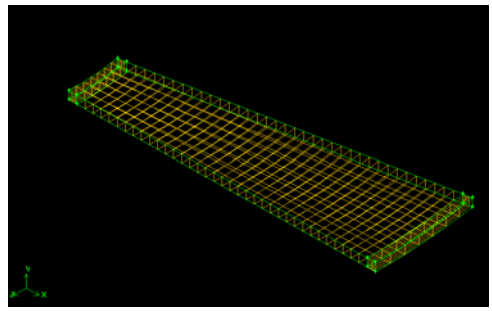
*Thermal couple 1, 3 and 5 are in the same axial level, the same as thermal couple 4 and 6. ** It is actually the entrained air mass flow rate.

VBA Heat Transfer Model Validation: geometry

Preheat Schematic



3 layers mesh in GAMBIT*



	VBA and FLUEMT Model nodes
inner glaze coating layer	4
wall refractory	37
outer glaze coating layer	4

* Use GAMBIT 2.2.30 software.

3-D FLUENT Setting:

Transient 3-layer Wall Model

Model	Energy
Momentum Schemes	2nd order upwind
Energy Schemes	2nd order upwind
Transient Formulation	1st order implicit

B.C.:

Inner SEN Wall	Free stream temperature 600degC heat transfer coefficient 70 W/m^{2}K
Outer SEN Wall	Free stream temperature 20degC heat transfer coefficient 20 W/m^{2}K

Time step: 1s **Total mesh: 308cells, 720 nodes**

Computational domain: axisymmetric, 1/36 circle of SEN

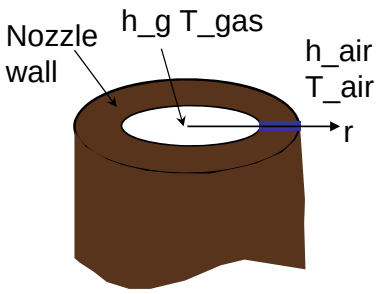
Test Condition of FLUENT 3D Transient Model and VBA Model

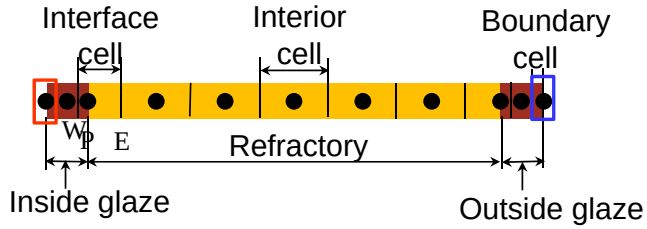
Input conditions

Test conditions		Input value	
Initial temperature		20℃	
Inner gas temperature		600 ℃	
Outer air temperature		20 ℃	
Inner heat transfer coefficient		70 W/m^{2}K	
Outer heat transfer coefficient		20 W/m^{2}K	
Inner radius		38 mm	
Thickness of glaze layer		1 mm	
Outer radius		76 mm	
Refractory	Heat conductivity	20 W/m K	
	Density	2460 kg/m^3	
	Specific heat	1500 J/kg K	
Glaze		**Case 1** (no glaze)	**Case 2**
	Heat conductivity	20 W/m K	1 W/m K
	Density	2460 kg/m^3	2400 kg/m^3
	Specific heat	1500 J/kg K	1000 J/kg K

Governing equation & boundary conditions for VBA Model

3-D Schematic of Nozzle





Governing Heat Transfer Equation

$$\frac{\partial}{\partial t}(\rho C_p T) = \frac{1}{r}\frac{\partial}{\partial r}(rk\frac{\partial T}{\partial r})$$

Boundary conditions

1→ ←2 $\rho C_p V \frac{\partial T}{\partial t} = -kA_2 \frac{\partial T}{\partial r}|_2 + h_g A_1 \Delta T|_1$

1→ ←2 $\rho C_p V \frac{\partial T}{\partial t} = kA_1 \frac{\partial T}{\partial r}|_1 - h_a A_2 \Delta T|_2$

Discretized Finite-Volume Equations

Interior cell governing equation

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

Inner boundary cell governing equation

$$T_1^{n+1} = \left(1 - \frac{2k\Delta t}{\rho C_p r\Delta r^2}\left(r + \frac{\Delta r}{2}\right) - \frac{2\Delta t h_g}{\rho C_p\Delta r}\right)T_1^n + \frac{2\Delta t h_g}{\rho C_p\Delta r}T_2^n + \frac{2k\Delta t}{\rho C_p r\Delta r^2}\left(r + \frac{\Delta r}{2}\right)T_{gas}$$

Outer boundary cell governing equation

$$T_m^{n+1} = \left(1 - \frac{2\Delta t k}{\rho C_p r\Delta r^2}\left(r - \frac{\Delta r}{2}\right) - \frac{2\Delta t h_a}{\rho C_p\Delta r}\right)T_m^n + \frac{2\Delta t k}{\rho C_p r\Delta r^2}\left(r - \frac{\Delta r}{2}\right)T_{m-1}^n + \frac{2\Delta t h_a}{\rho C_p\Delta r}T_{air}$$

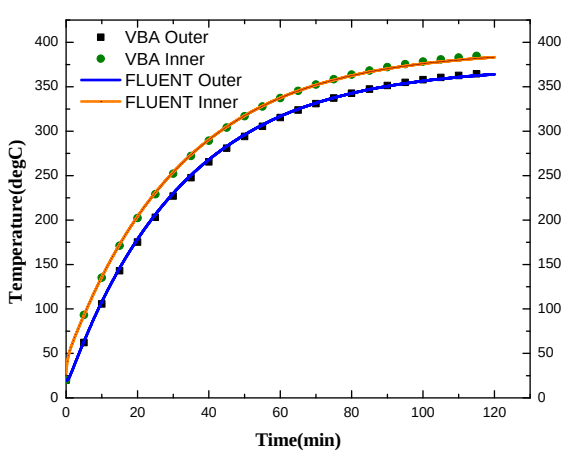
Interface cell governing equation

$$T_p^{n+1} = \left[1 - \frac{2\Delta t}{r_e^2 - r_w^2}\left(\frac{k_e r_e}{\rho C_p\Delta r_{PE}} + \frac{k_w r_w}{\rho C_p\Delta r_{PW}}\right)\right]T_p^n + \frac{2\Delta t k_w r_w}{(r_e^2 - r_w^2)\rho C_p\Delta r_{PW}}T_{p-1}^n + \frac{2\Delta t k_e r_e}{(r_e^2 - r_w^2)\rho C_p\Delta r_{PE}}T_{p+1}^n$$

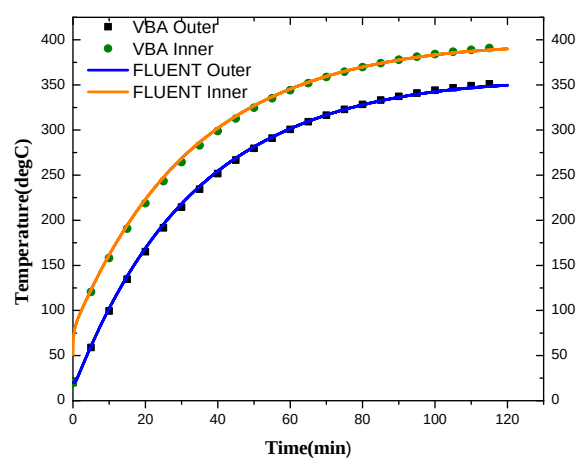
The derivation is in Yonghui's VBA model governing equations20120408.docx.

Results: Case 1&Case 2

Comparison of 3-layer VBA model and 3-D FLUENT model predictions of transient temperature in **1-layer** nozzle at inner and outer surface

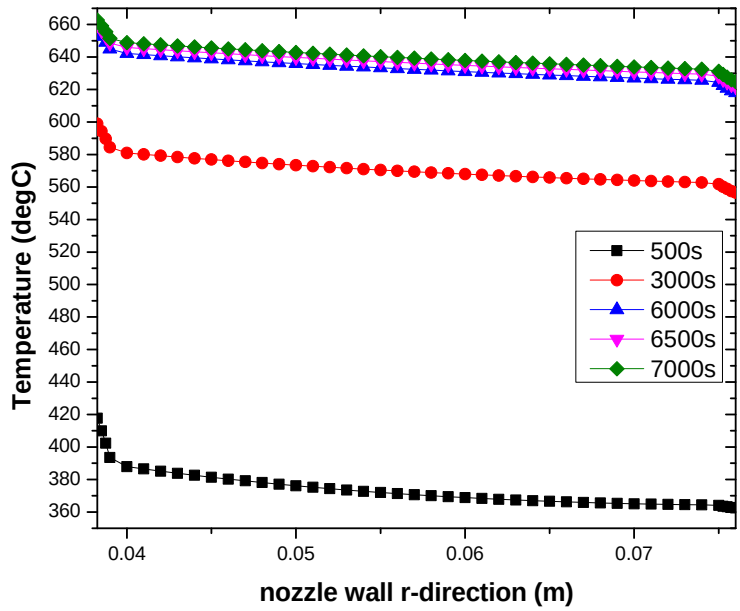


Comparison of 3-layer VBA model and 3-D FLUENT model predictions of transient temperature in **3-layer** nozzle at inner and outer surface



Result: Case 2 temperature at different time

Glaze coating and wall refractory 3-layer case r-direction along nozzle wall temperature evolve histories



Temperature dependent thermal properties feature

- Validate VBA heat transfer model in preheating and cool down processes with FLUENT Model.
- FLUENT User Defined Function is used for the inner gas/air temperature (wall boundary) and heat transfer coefficients.

The input conditions come from experiment Run 2

	Preheat	Cool down
Inner gas temperature(K)	1673.15	T=20+126exp(-0.000292(current time –preheat time))
Outer air temperature(K)	293.15	293.15
Inner h_convection (W/m²K)	400	20
Outer h_convection(W/m²K)	400	20
Initial temperature(K)	293.15	293.15

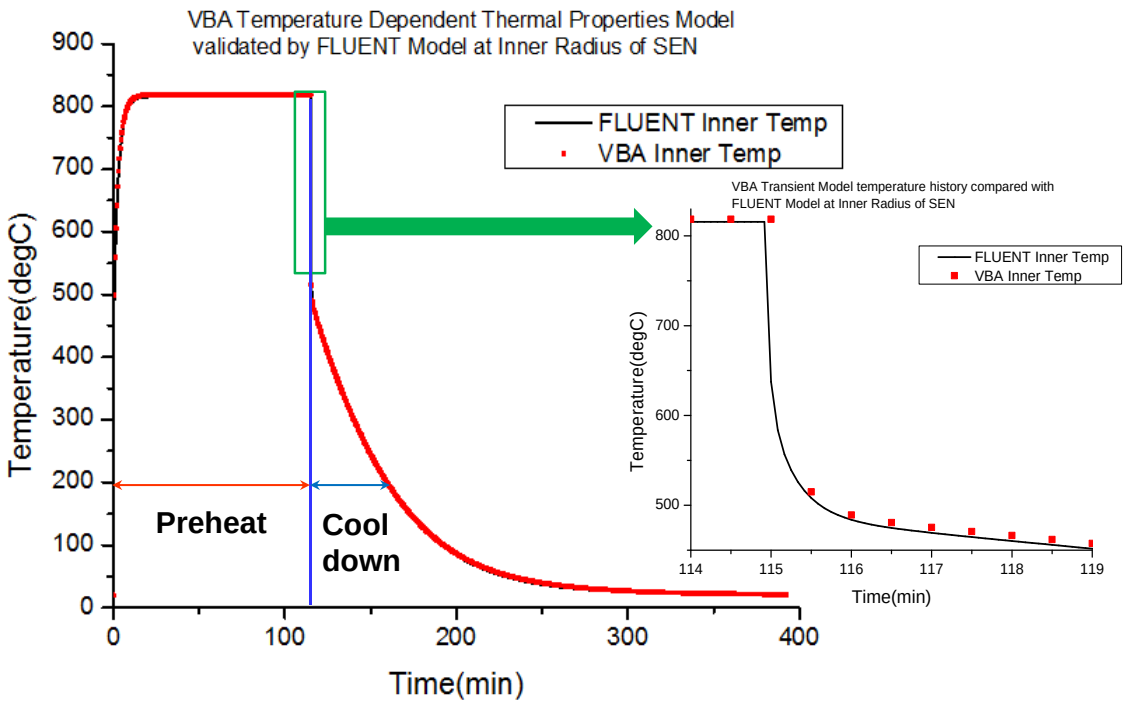
Glaze material

Material	Glaze		
Density	2000 kg/m³		
Properties used in VBA	Temperature(degC)	Thermal conductivity(W/m K)	Specific Heat (J/kg K)
	25	0.8555	835.0425
	200	1.2926	1031.0565
	550	1.5409	1345.6037
	1075	0.8312	1768.4251
	1425	0.0119	2130.1868
Properties used in FLUENT (SI unit)	$k(T)=-0.4856+0.0059T-(5e-6)T^2+(e-9)T^3$		
	$Cp(T)=406.77+1.6781T-0.0009T^2+(3e-7)T^3$		

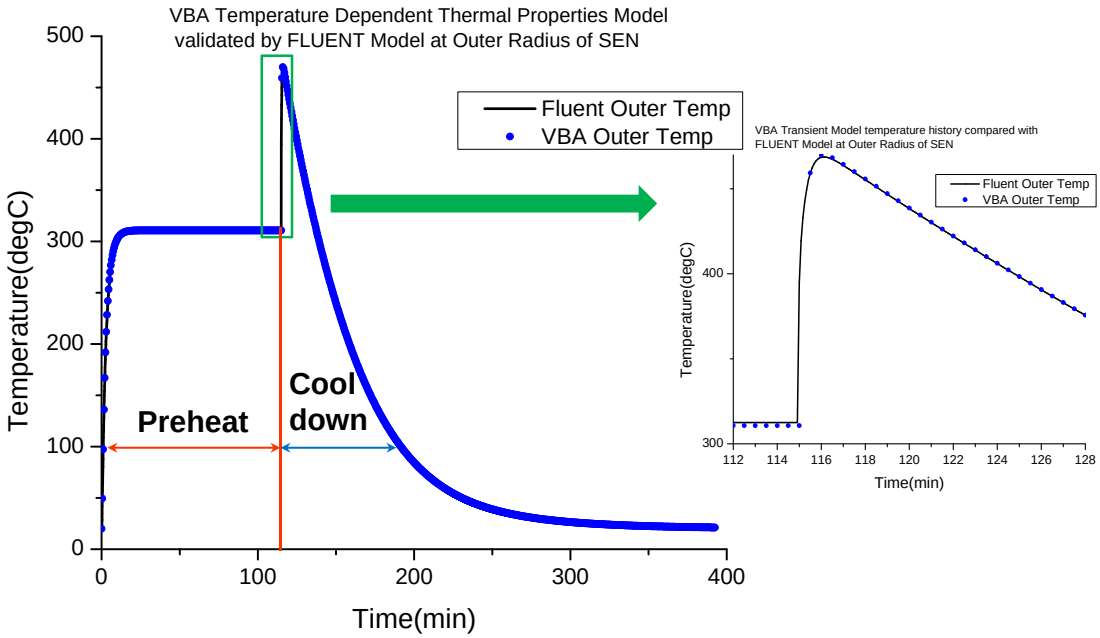
Refractory material

Material	Doloma Graphite		
Density	2330 kg/m^3		
Properties used in VBA	Temperature(degC)	Thermal conductivity(W/m K)	Specific Heat (J/kg K)
	25	26.4528	753.3534
	500	21.8180	1252.3953
	750	19.7412	1360.4835
	1000	17.9143	1422.9122
	1500	15.0106	1598.2917
Properties used in FLUENT (SI unit)	$k(T)= 29.823-0.0119T+(2e-6)T^2$		
	$Cp(T)=125.61+2.6275T-0.0019T^2+(5e-7)T^3$		

Results: validated Temperature history in FLUENT and VBA



Results: validated Temperature history in FLUNET and VBA



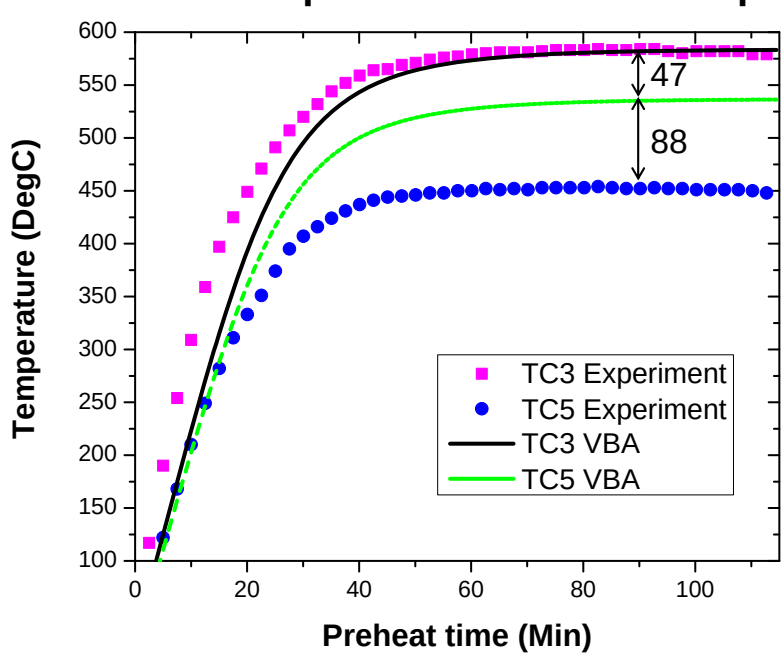
Compared VBA Model with Experiment data

VBA Model input conditions for Run2 (Experiment)

VBA Input conditions	Value	Source
Inner gas temperature	885-432*Exp (-time in second/1066) (degC)	Concluded from gas temperature histories from experiment
Outer air temperature	19 (degC)	LWB Experiment data
Inner h_convection	50.89 W/ m^2K	Combustion Model result
Outer h_convection	35.25 W/ m^2K	Combustion Model result
Emissivity of outer glaze	0.82	LWB Emissivity Testing
Emissivity of inner flame	1	Black body of inner SEN
Thermal properties	Slide 29 tables	LWB measurements
Preheat time	115	LWB Experiment data

Compare VBA and Experiment Results

Preheat temperature histories comparison



Axial heat flux causes the difference.

Conclusion

- A fluid flow / heat transfer / combustion model has been developed and linked with VBA Model (via heat transfer coefficients) to predict behavior of nozzle during preheating.
- The temperature predictions from combustion model reasonably match with experiment measurement.
- The combustion model / SEN model could be investigated in more detail (for other fuels, air mixtures, etc.) with parametric studies to optimize preheating times and provide guidelines for different conditions.
- The SEN model is the ready to apply to investigate casting.

Acknowledgements

- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Tata Steel, Goodrich, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech/ Posco, SSAB, ANSYS-Fluent)
- Rob Nunnington, LWB Refractories
- National Center for Supercomputing Applications (NCSA) at UIUC – “Tungsten” cluster

Reference

[1] PB10 SEN Temperature Data for CCC Heat Flow Model, Magnesita Refractories Research report

[2] Varun K. Singh, User-friendly model of heat transfer in submerged entry nozzle during preheating, cool down and casting

[3] GAMBIT 2.2.30 software

[4] Use FLUENT 13.0 software

[5] FLUENT theory guide

[6] CFD-Post software

Nomenclature

Symbol	Variable	Unit
V	volume	m^3
t	time	s
Δt	time step	s
r	radius	m
r_w	west node radius	m
r_e	east node radius	m
Δr	neighbor node distance	m
Δr_{PE}	east side node distance	m
Δr_{PW}	west side node distance	m
T	temperature	℃
T_p^{n+1}	temperature of node p at new(n+1) time step	℃
T_p^n	temperature of node p at old (n) time step	℃
T_{gas}	inside gas temperature	℃
T_{air}	outside air temperature	℃
ρ	density	kg/m^3
C_p	specific heat	J/kg K
k	heat conductivity	W/m K
k_w	west side cell conductivity	W/m K
k_e	east side cell conductivity	W/m K
h_g	inside gas convective coefficient	W/m^2K
h_a	out air convective coefficient	W/m^2K