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User-friendly model of heat transfer in submerged entry nozzles during preheating, cool down and casting

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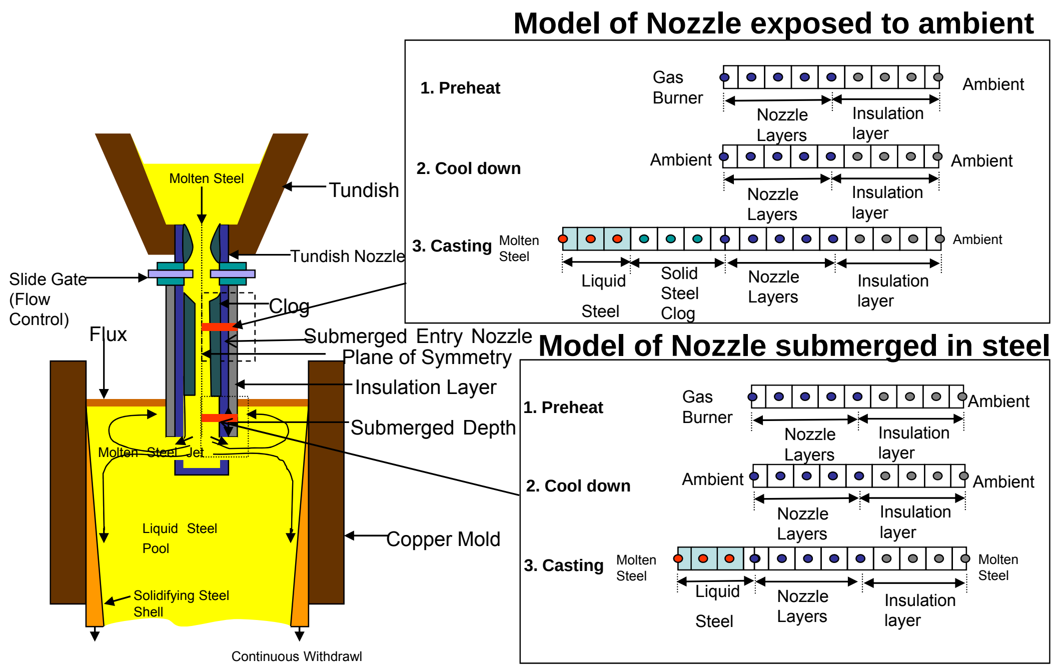
Objectives

- Develop a user friendly spreadsheet based tool to calculate the heat transfer coefficients and flame temperature during preheating of the nozzle.
- Develop a user friendly spreadsheet based tool to model the heat transfer in submerged entry nozzles during the three stages: preheat, cool down and casting.

Continuous Casting Consortium

Model & computational domain



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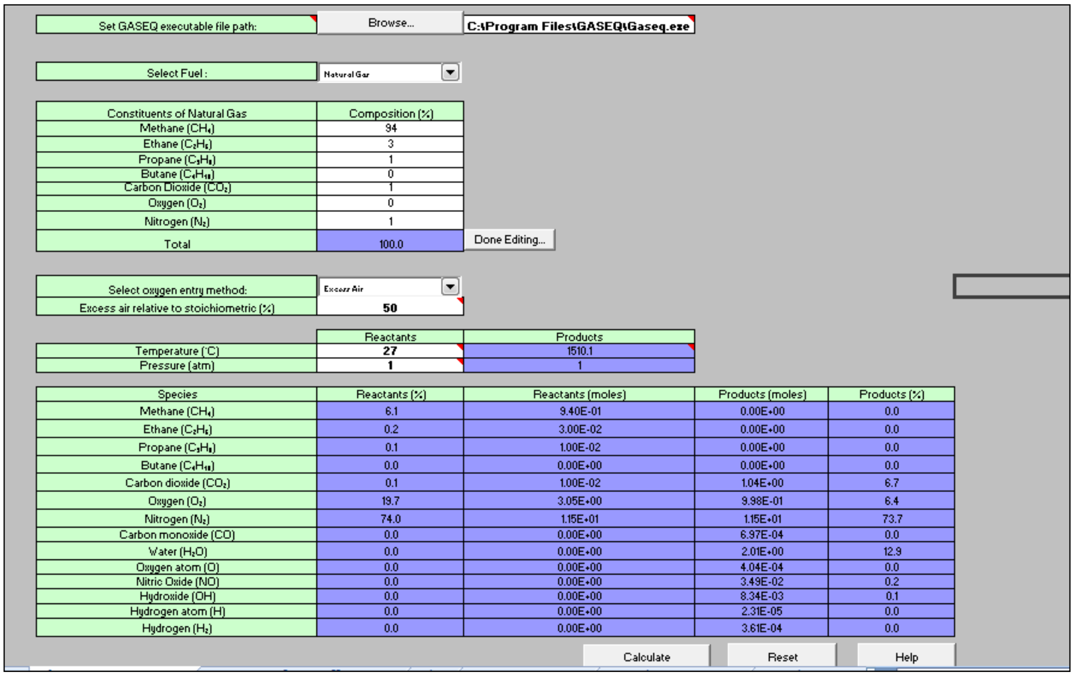
Models Developed

- Flame Temperature Calculation Model
- Heat Transfer Coefficients Calculation Model
- Model for heat transfer in the refractory during the three stages:
  - preheat,
  - cool down
  - casting
    - Ambient slice
    - Submerged slice.

Flame Temperature Calculation Model – Input Page



Set GASEQ executable file path:	Browse...	C:\Program Files\GASEQ\Gaseq.exe
Select Fuel :	Natural Gas	

Constituents of Natural Gas	Composition (%)
Methane (CH_4)	94
Ethane (C_2H_6)	3
Propane (C_3H_8)	1
Butane (C_4H_{10})	0
Carbon Dioxide (CO_2)	1
Oxygen (O_2)	0
Nitrogen (N_2)	1
Total	100.0

Done Editing...

Select oxygen entry method:	Excess Air
Excess air relative to stoichiometric (%)	50

	Reactants	Products
Temperature (°C)	27	1510.1
Pressure (atm)	1	1

Species	Reactants (%)	Reactants (moles)	Products (moles)	Products (%)
Methane (CH_4)	6.1	9.40E-01	0.00E+00	0.0
Ethane (C_2H_6)	0.2	3.00E-02	0.00E+00	0.0
Propane (C_3H_8)	0.1	1.00E-02	0.00E+00	0.0
Butane (C_4H_{10})	0.0	0.00E+00	0.00E+00	0.0
Carbon dioxide (CO_2)	0.1	1.00E-02	1.04E+00	6.7
Oxygen (O_2)	19.7	3.05E+00	9.98E-01	6.4
Nitrogen (N_2)	74.0	1.15E+01	1.15E+01	73.7
Carbon monoxide (CO)	0.0	0.00E+00	6.97E-04	0.0
Water (H_2O)	0.0	0.00E+00	2.01E+00	12.9
Oxygen atom (O)	0.0	0.00E+00	4.04E-04	0.0
Nitric Oxide (NO)	0.0	0.00E+00	3.49E-02	0.2
Hydroxide (OH)	0.0	0.00E+00	8.34E-03	0.1
Hydrogen atom (H)	0.0	0.00E+00	2.31E-05	0.0
Hydrogen (H_2)	0.0	0.00E+00	3.61E-04	0.0

Calculate Reset Help

Calculation of Flame temperature and heat transfer coefficients

- User can select from the following gases as fuel: Methane, hydrogen, propane, natural gas, blast furnace gas and acetylene.
- The species considered are: CO_2, O_2, O, CO, H_2O, N_2, NO, OH, H, H_2
- For natural gas and blast furnace gas, user can specify the percentage of various constituents (natural gas: mathane – 94%, ethane – 3%, propane – 1%, butane – 0%, CO_2 – 1%, O_2 – 0%, N_2 – 1%)
- Reactants temperature and pressure need to be entered.
- The reaction is a constant pressure process.
- The user can choose between excess air and oxygen enrichment.
- The amount of excess air or air enrichment needs to be specified.
- The flame temperature calculated for the above composition of natural gas with 50% excess air was found to be 1510 °C.

Heat Transfer Coefficients

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

Flame Temperature	1510.1	°C
Outside Surface Temperature	828.7	°C
Nozzle Orifice Area	4.42E-01	$inch^2$
Characteristic diameter	0.0732	m
Gas Pressure	9	PSI
Friction Factor	0.03	m/m
Gas Pressure	6.21E+04	Pa
Nozzle Orifice Area	2.85E-04	m^2
Gas Density	1.45E-01	kg/m^3
Velocity	9.24E+02	m/s
Mass flow Rate	3.83E-02	kg/s
Free Convection	7.64	W/m^2-K
Forced Convection	72.45	W/m^2-K

Calculate

Forced Convection (molten steel flowing on inside of the nozzle)

Casting Speed	4	ton/minute
Density of Steel	7015	kg/m^3
Thermal Conductivity of Steel	33	W/(m-k)
Dynamic Viscosity of Steel	0.0055	Ns/m^2
Thermal Diffusivity	6.10E-06	m^2/s
Casting Speed	2.26	m^3/s
Reynolds Number	2.11E+05	
Prandtl Number	1.29E-01	
b	7.96E-01	
a	8.22E-01	
Nusselt Number	7.45E+01	
Heat Transfer Coefficient	33594.11	W/m^2-K

Sleicher and Rouse Equation

$$Re = \frac{2ur}{\upsilon} \qquad Pr = \frac{\upsilon}{\alpha}$$

$$b = \frac{1}{3} + 0.5\,Exp(-0.6 * \Pr) \qquad a = 0.88 - \frac{0.24}{4 + Pr}$$

$$Nu = 5 + 0.015\,Re^a Pr^b \qquad h = \frac{Nu.k}{2r}$$

Heat Transfer Coefficients

- Free Convection to ambient:
  - The Churchill and Chu [1] equation for flow over a vertical flat plate is used

$$Nu_{avg} = \left\{ 0.825 + \frac{\left[0.387\,Ra^{1/6}\right]}{\left[1 + \left(\frac{0.429}{Pr}\right)^{9/16}\right]^{8/27}} \right\}^2$$

- Forced Convection from flame:

  The Petukhov, Kirillov, and Popov [1] is used

$$Nu = \frac{\left[(f/8)\,\mathrm{Re}_D\,\Pr\right]}{\left[1.07 + 12.7(f/8)^{1/2}(\Pr^{2/3} - 1)\right]}$$

- The forced heat transfer coefficient was calculated to be 72.5 W/m^2K.
- The free heat transfer coefficient was calculated to be 7.6 W/m^2K

- Sleicher and Rouse equation was used to calculate the forced convection heat transfer coefficient from molten steel flowing on the inside of the nozzle.

Properties of mixture of gases in combustion products

- Thermal conductivity of the mixture of gases is calculated using Saxena and Mason [3]:

$$\lambda_m = \sum_{i=1}^{n} \frac{y_i \lambda_i}{\sum_{j=1}^{n} y_j A_{ij}}$$

Where λ_m = the thermal conductivity of the gas mixture
λ_i = the thermal conductivity of pure i
y_i, y_j = mole fractions of component i and j

$$A_{ij} = \frac{\left[1 + (\eta_i / \eta_j)^{1/2} (M_j / M_i)^{1/4}\right]^2}{[8(1 + M_i / M_j)]^{1/2}}$$

$$A_{ji} = \frac{\eta_j}{\eta_i} \frac{M_i}{M_j} A_{ij}$$

Where η_i, η_j are the viscosities of pure i and j respectively

And M_i, M_j are the molecular weights of pure i and j

- Thermal diffusivity, kinematic viscosity, density and specific heat are calculated using the particle mixture rule.

Heat Transfer Model for the refractory – Main Page

Heat Transfer Model of skull clogging for variable layers

Geometry of Nozzle		
Outer Radius of Refractory	78	mm
Enter Number of layers	3	
Emmissivity	0.5	

Clear

Assign Refractory Properties

Preheat					
Ambient Temperature	24.0	°C			
Initial Nozzle Temperature	9.0	°C			
FlameTemperature	1510.0	°C			
Internal heat transfer Coefficient (forced)	72.5	W/(m²K)			
External heat transfer Coefficient (free)	7.64	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

Preheat Simulation

View Preheat Plots

Cooldown					
Ambient Temperature (Outside)	24.0	°C			
Ambient Temperature (Inside)	24.0	°C			
Internal heat transfer Coefficient	7.64	W/(m²K)			
External heat transfer Coefficient	7.64	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

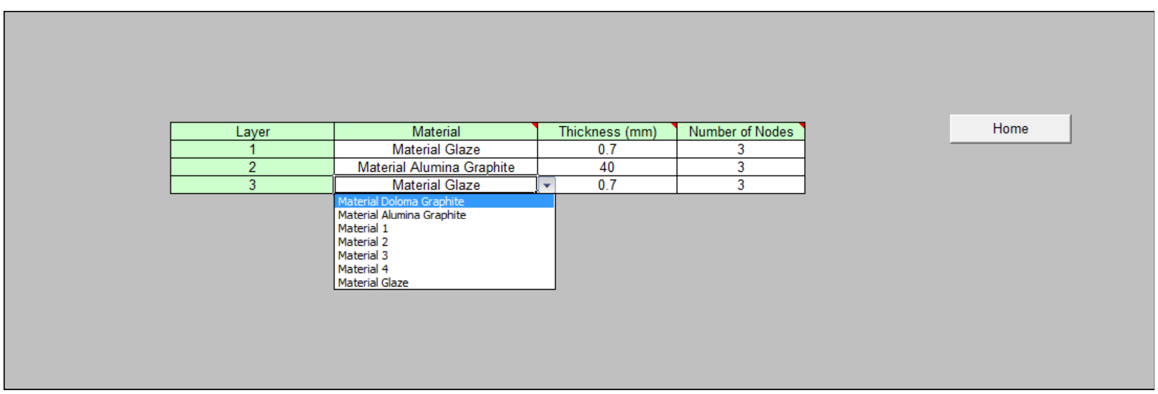
Cooldown Simulation

View Cooldown Plots

Heat Transfer Model for the refractory – Features

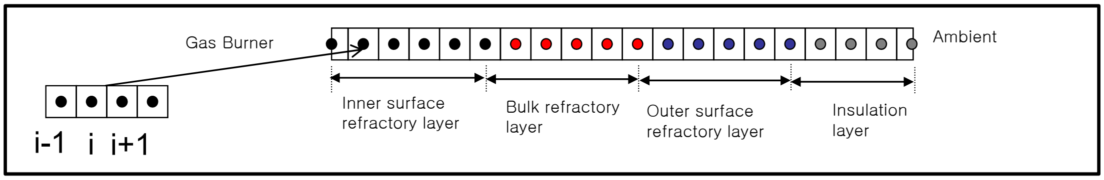
- User can enter the number of layers he wants in the model.
- Each layer can have different thickness and different number of nodes.
- The user can choose at what times the results have to be plotted.
- User can select the nodes where the results are to plotted.

Heat transfer model – assign refractory properties



- The table gets populated based on the number of layers entered by the model.
- User can select which material should be assigned to each layer by choosing from the drop down menu (which get automatically populated to show all the materials in the excel file)

Governing Equation and finite difference equation for interior nodes



- Heat conduction equation in cylindrical co–ordinates [1]

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

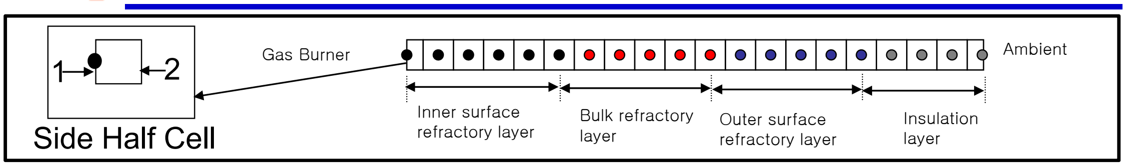
- Using Taylor series [1] expansion, the equation is discretized as:

$$\Longrightarrow \rho C_p \frac{\partial T}{\partial t} = \frac{k}{r}\left[\frac{\partial T}{\partial r} + r\frac{\partial^2 T}{\partial r^2}\right] \qquad \Longrightarrow \frac{\partial T}{\partial t} = \alpha\left[\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right]$$

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

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

Finite Difference Equations (Side nodes with convection)



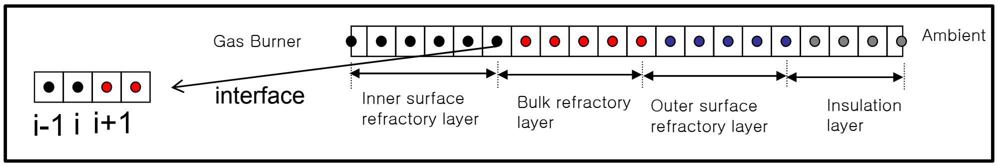
- Heat balance on side half cell gives:

$$\rho C_p V\frac{\partial T}{\partial t} = -kA_2\frac{\partial T}{\partial r}\Big|_2 + hA_1\Delta T\Big|_1$$

$$\Longrightarrow \rho C_p\frac{r\Delta r}{2}\frac{T_i^{n+1} - T_i^n}{\Delta t} = k\left(r + \frac{\Delta r}{2}\right)\left(\frac{T_i^n - T_{i+1}^n}{\Delta r}\right) + hr\left(T_{ambient} - T_i^n\right)$$

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

Finite Difference Equations (Interface Nodes)



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

$$\Rightarrow \rho C_p \frac{T_i^{n+1} - T_i^n}{\Delta t} = \frac{1}{\Delta r r_i}\left[r_{i+1/2} k_2 \frac{\partial T}{\partial r}\bigg|_{i+1/2} - r_{i-1/2} k_1 \frac{\partial T}{\partial r}\bigg|_{i-1/2} \right]$$

$$\Rightarrow \rho C_p \frac{T_i^{n+1} - T_i^n}{\Delta t} = \frac{1}{\Delta r r_i}\left[\left(r + \frac{\Delta r}{2}\right) k_2 \frac{T_{i+1}^n - T_i^n}{\Delta r} - \left(r - \frac{\Delta r}{2}\right) k_1 \frac{T_i^n - T_{i-1}^n}{\Delta r}\right]$$

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

Steel Shell Solidification Model

- Enthalpy formulation of the transient 1-D heat conduction equation is solved:

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

- Top row temperatures:

$$T_i = T_{pour}$$

- Top row enthalpies [2]:

$$H_i = C_p * T_{pour} + L_f * \mathrm{int}\left(\frac{T_{pour}}{T_{solidus}}\right)$$

where L_f is the latent heat of fusion.

Steel Shell Solidification Model

- Enthalpy of interior nodes:

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

- Enthalpy of side nodes with convection:

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

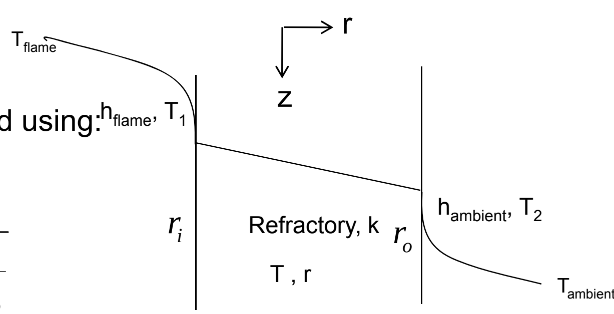
- After the enthalpy has been calculated the temperatures are then calculated using [2] :

$$T_i = \min\left[\frac{H_i}{C_p}, \max\left\{\frac{H_i - L_f}{C_p}, T_{sol}\right\}\right]$$

Validation of Steady State Aspect of the Model

- Compared the results of the simulation when it reaches steady state with analytical Solution.
- Governing equation for Analytical solution [1]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)=0$$



- Heat flux through the nozzle is calculated using:

$$q = \frac{T_{flame} - T_{ambient}}{\frac{1}{h_{flame} r_i} + \frac{\ln(r_o / r_i)}{k} + \frac{1}{h_{ambient} r_o}}$$

$$r_i = r_o - t$$

- Finally, the temperatures in the nozzle are :

$$T_1 = T_{flame} - \frac{q}{h_{flame} r_i}$$

$$T_2 = T_{ambient} + \frac{q}{h_{ambient} r_o}$$

$$T = T_1 - \frac{q}{k}\ln\left(\frac{r}{r_i}\right)$$

Simulation conditions for validation of steady state aspect of the model

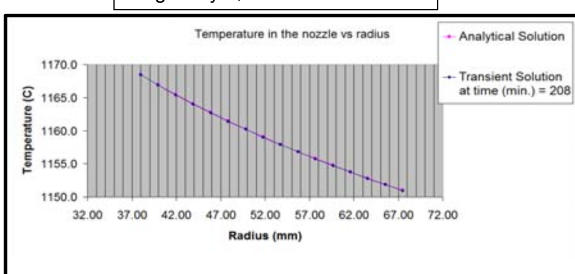
Label	Symbol	Value	Units
Outer Radius of Refractory	r_o	67.5	mm
Bulk Refractory Wall Thickness	t	29.5	mm
Initial Nozzle Temperature	$T_{intital}$	27*	°C
Ambient Temperature	$T_{ambient}$	27	°C
Flame Temperature	T_{flame}	1460	°C
Internal Convection heat transfer Coefficient (Forced)	h_{flame}	50	$W/(m^2K)$
External Convection heat transfer Coefficient (Free)	$h_{ambient}$	7.3	$W/(m^2K)$
Thermal Conductivity	K	18.21	W/m-K
Specific Heat	C_p	804*	J/kg-K
Density	ρ	2347	kg/m^3
Stefan Boltzman's Constant	σ	5.67E-8	
Emmissivity	ε	0.96	

* Parameters required by transient simulation method

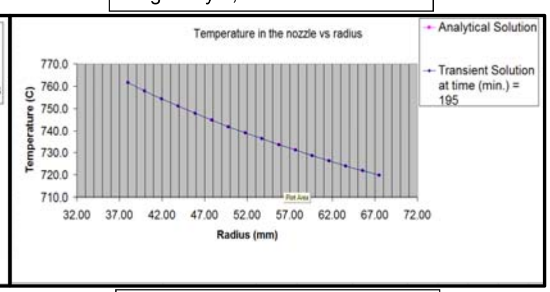
Validation – Steady state aspect of the model

- The results of the simulation are in good agreement with that of the analytical solution

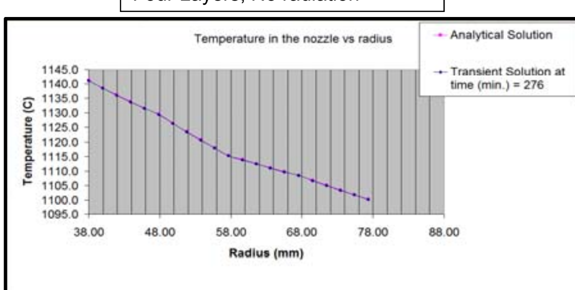
Single Layer, No radiation



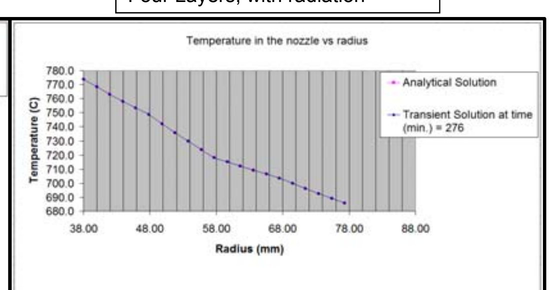
Single Layer, with radiation



Four Layers, No radiation



Four Layers, with radiation



Validation of transient aspect of the model

- Compare the results of the simulation with that of the lumped thermal heat capacity model.
- System undergoing a transient thermal response to a heat transfer process has a nearly uniform temperature and small differences of temperature within the system can be ignored.
- The model is valid only if the Biot number (hL/k) < 0.1
- The governing equation is [1]

$$\rho V C_p \frac{dT}{dt} = -hA(T - T_e)$$

- To solve this equation, one initial condition is required:

  t=0: $T=T_o$.

  Solving the equation, the temperature at any time,t can be calculated from:

$$\frac{T - T_e}{T_o - T_e} = e^{-(hA/\rho V C_p)t}$$

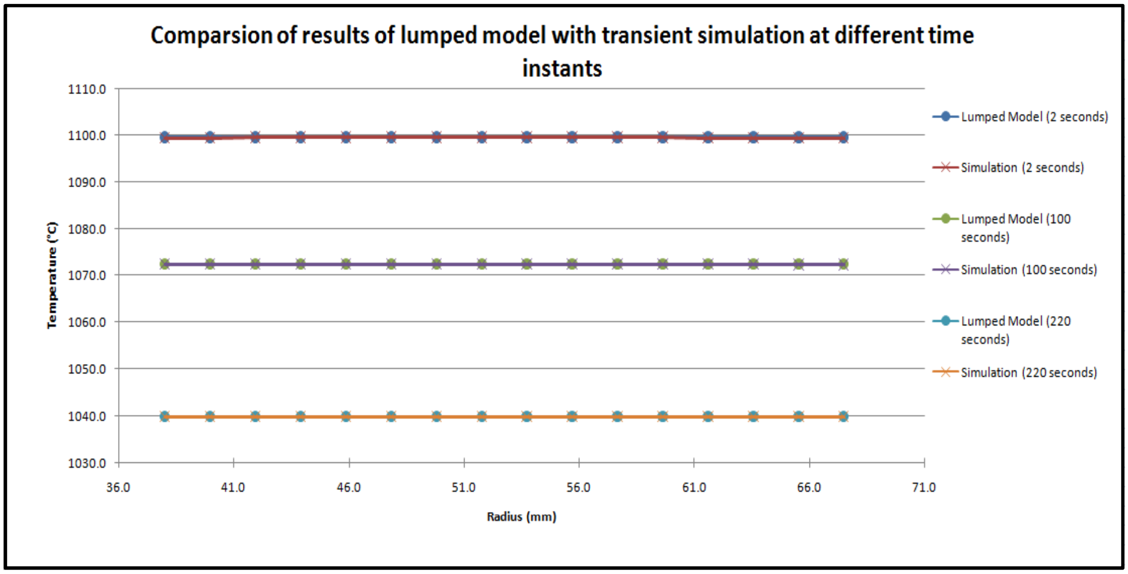
where T_o is the initial surface temperature, T_e is the ambient temperature.

Simulation Parameters – Validation of transient aspect of the model

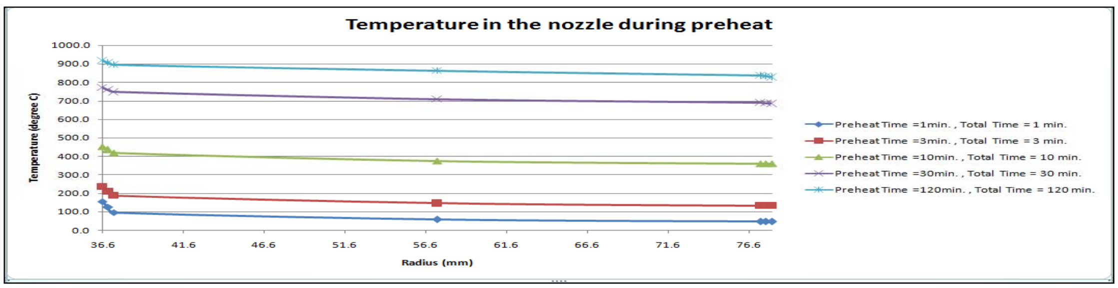
Label	Symbol	Value	Units
Outer Radius of Refractory	r_o	67.5	mm
Bulk Refractory Wall Thickness	t	29.5	mm
Initial Nozzle Temperature	$T_{intital}$	1100	°C
Ambient Temperature	$T_{ambient}$	27	°C
External Convection heat transfer Coefficient (Free)	$h_{ambient}$	7.3	W/(m²K)
Thermal Conductivity	K	1000	W/m-K
Specific Heat	C_p	804	J/kg-K
Density	ρ	2347	kg/m³
Stefan Boltzman's Constant	σ	5.67E-8	
Emmissivity	ε	0.96	

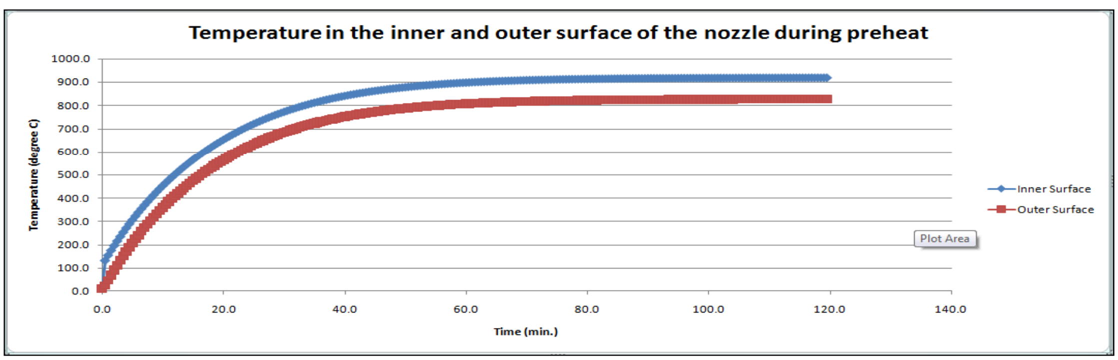
Comparison of Results of lumped model and transient simulation

• The results of the simulation are in good agreement with that of the lumped thermal heat capacity model

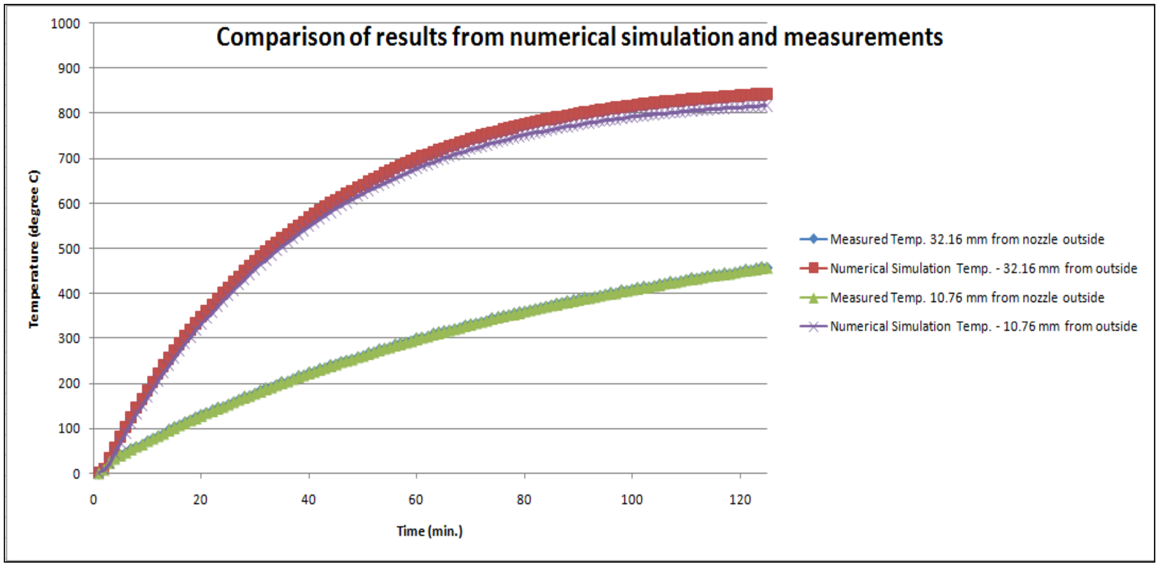


Output page of the tool

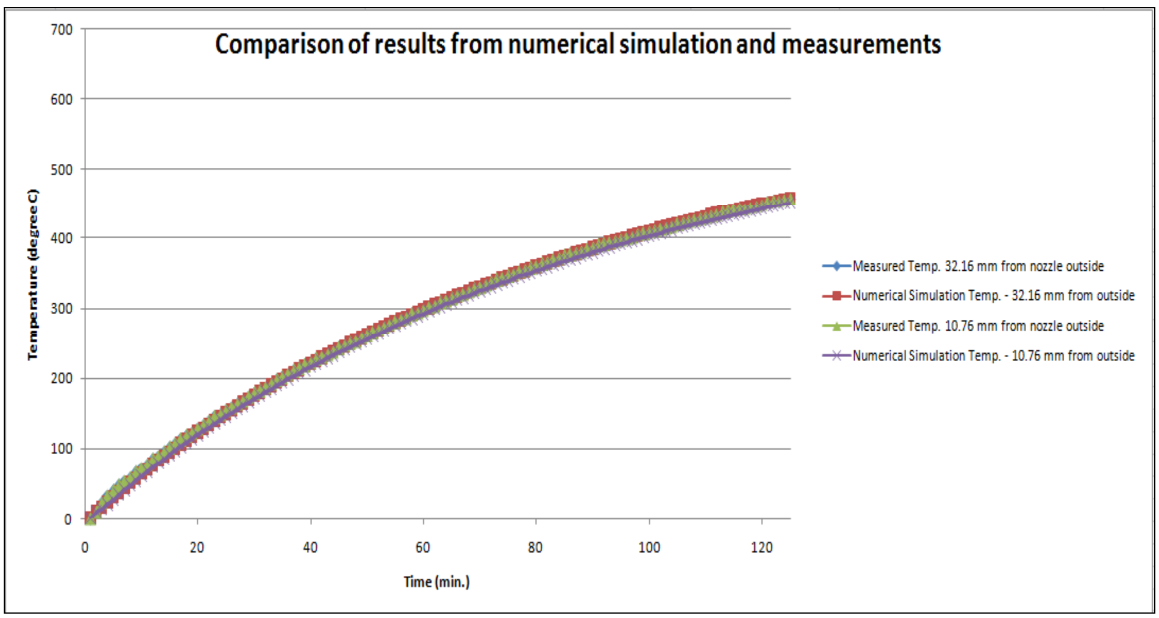




Comparison with measurements (inside heat transfer coefficient = 72 W/m^2-K)



Comparison with measurements (inside heat transfer coefficient = 18 W/m^2-K, emissivity = 0.5)



Parametric Study

Parameters	Highest Temperature	Difference in temp. between inner and outer surface
Forced Convection = 72 W/m^2-K, emissivity = 0.5	920 °C	90 °C
Forced Convection = 18 W/m^2-K, emissivity = 0.5	585 °C	30 °C
Thermal Conductivity is halved	954 °C	150 °C
Emissivity increased to 0.9	850 °C	100 °C
Specific Heat is doubled	954 °C	100 °C

Conclusions

- The temperature in the inner surface of the nozzle reached 900 °C after a preheat time of 2 hours. If the inside heat transfer coefficient is reduced to 18 W/m^2-K the temperature in the inner surface of the nozzle is 585 °C. Results from numerical simulation match those of experiments for this case.
- The tool can be used to predict the temperatures in the nozzle during different stages of preheat, cool down and casting.
- The tool can be used to calculate the flame temperature and heat transfer coefficients for different fuels and varying composition.
- Air entrainment should be decreased, because excess air reduces the flame temperature.

References

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2. Thomas, B.G. and B. Ho, "Spread Sheet Model of Continuous Casting," Journal of Engineering for Industry, ASME, New York, NY, Vol. 118, No. 1, 1996, pp. 37-44.
3. Poling, B.E., O'Connell J.M., and Prausnitz, J.M., 2001, *The Properties of Gases and Liquids,* McGraw-Hill, New York.
4. Moran, J.M., and Shapiro, H.N., 2004, *Fundamentals of Engineering Thermodynamics,* John Wiley and Sons, New York.
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