



ANNUAL REPORT 2010

UIUC, August 12, 2010

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

Varun Kumar Singh, B.G. Thomas



Department of Mechanical Science and Engineering University of Illinois at Urbana-Champaign



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.



Model & computational domain





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.

4

.

Set GASEQ executable fle path Browse. CxProgram FilestGASEQRGaseq.ee Set GASEQ executable fle path Browse. CxProgram FilestGASEQRGaseq.ee Set GASEQ executable fle path Browse. Set GASEQ executable fle path Set GASEQ executable fle path Browse. Set GASEQ executable fle path Set GASEQ executable fle path Browse. Set GASEQ executable fle path Set GASEQ executable fle path Browse. Set GASEQ executable fle path Set GASEQ executable fle path Browse. Set GASEQ executable fle path Set GASEQ executable fle path Browse. Dome Edition. Set GASEQ executable fle path Browse. Dome Edition. Set Gasegen entry method Set		Flam	ie iemp	erat	ure
Set GASEQ esecutable file path: Browse C:tProgram FilestGASEQtGaseq.exe Set GASEQ esecutable file path: Drowse C:tProgram FilestGASEQtGaseq.exe Set GASEQ esecutable file path: Drowse C:tProgram FilestGASEQtGaseq.exe Set Constituents of Natural Gas Composition (2) Methane (CH4) 3 Drogram (CH4) 1 Celefont Boorde (Cb1) 1 Celefont Boorde (Cb1) 1 Drogram (CH4) 0 Celefont Boorde (Cb1) 1 Celefont Boorde (Cb1) 1 Celefont Boorde (Cb1) 1 Drogram (CH4) 1 Droducts (moles) Products (moles) P			- N/ I - I		
Set BASEQ executable file path: Browse CxProgram FilestBASEQ4Baseq.ese Set BASEQ executable file path: Neverifier Set Basequestion (2) Neverifier Methane (CH) 94 Ethere (CH) 1 Botane (CH) 1 Done Editing. Executable to stochlometric (S) Select ongen entry method Executable Excess al relative to stochlometric (S) Select ongen entry method Temperature (C) 22 Pressure (arm) 1 1 1 Species Prestants (C) Pressure (arm) 1 1 1 Species Prestants (C) Products (moles) Products (CA) Obsection 0.0005-00 0.001 Dropone (CH) 0.0 0.0005-00 </th <th>Laic</th> <th>llatio</th> <th>n iviodei</th> <th>– IN</th> <th>but F</th>	Laic	llatio	n iviode i	– IN	but F
Set GASEQ executable file path: Browse CxProgram FilestGASEQtGaseq.ese Seted Fuel: NeurolGe • Constituents of Natural Gas Composition (2) • Methane (CH) 94 • Ethere (CH) 1 • Botane (CH) 1 • Organe (Ch) 0 • Carbon blook (CD) 1 • Object (Ch) 1 • Total 00.0 Done Editing Select orggen entry method • • Excess at relative to stockhometric (X) • • Species Prestants (X) Prevaluts (moles) Products (C) Pressure (arm) 1 1 1 Species Prestants (X) Prevaluts (moles) Products (X) Methane (CH) 6.3 9.446-01 0.006-00 0.0 Product (CA) 0.0 0.006-00 0.0 0.0 Butare (CH) 0.0 0.006-00 0.0 0.0 Propane (CH) <t< th=""><th></th><th></th><th></th><th></th><th></th></t<>					
Ort Ordect sectors in the part. C. It rogsmin The stored diverse is a store of the stored diverse is a store of the stored diverse is a store of the store of th	Sat GASEO avecutable (ile path	Browse	CalBrogram EilertG&SEDIGarog ere		
Select Fuel: Networks Constituents of Natural Gas Composition (%) Bithare (CH4) 94 Ethare (CH4) 1 Butare (CH4) 1 Obgen (C0-1) 1 Outgen (CH4) 1 Total 100.0 Done Editing	Set GASEQ executable file part.		C.II Togram Thesturio Equased.exe		
Select Fue: Neural Gas Constituents of Natural Gas Composition (%) Methane (CH ₁) 3 Propane (CH ₁) 1 Bitane (CH ₁) 0 Carbon Dioxide (CO) 1 Orggen (G) 0 Nitrogen (Na) 1 Total 100.0 Done Editing. 50 Select coggen entry method: Exerc Air Excess air relative to stoichiometric (%) 50 Pressure (am) 1 Species Reactants (%) Species Reactants (%) Species Reactants (%) Methane (CH ₁) 61 Methane (CH ₁) 0.0 Outpendout (CO) 0.00 Products (moles) Products (moles) Products (moles) Products (%) Methane (CH ₁) 0.1 1000E-00 0.0 Butane (CH ₁) 0.0 0.00E-00 0.0 Dispective (am) 1 100E-02 0.00E-00 0.0 Outpendout (CO) 0.1 </td <td>Octor Evel</td> <td></td> <td></td> <td></td> <td></td>	Octor Evel				
Constituents of Natural Gas Composition (%) Methane (CH) 34 Propane (CH) 3 Propane (CH) 1 Butane (CH) 1 Caraton Disoide (CO) 1 Origon (Na) 1 Drogen (CH) 1 Origon (Na) 1 Total 00.0 Done Editing	Select Fuel :	Natural Gaz 💌			
Constituents of Natural Las Composition (%) Methane (CH) 3 Ethane (CH) 1 Butane (CH) 1 Oragen (CH) 1 Oragen (CH) 1 Total 100.0 Done Editing 50 Select ouggen entsy method: 50 Excess ai relative to stochkiometric (X) 50 Resolution 1 Select ouggen entsy method: 50 Resolution 1 Select ouggen entsy method: 50 Resolution 1 Select ouggen entsy method: 50 Resolution 1 Species Resolution (X) Resolution 1 Species Resolution (X) Resolution 0.000E-00 Output 0.000E-00 Butane (CH) 0.1 Butane (CH) 0.1 Butane (CH) 0.1 Butane (CH) 0.1 Butane (CH) 0.0 Butane (CH) 0.0			1		
International (C+1) 3-4 Ethame (C+1) 3 Propane (C+1) 1 Butane (C+1) 0 Catbon Dioride (CD) 1 Droggen (0,1) 0 Nitrogen (Na) 1 Total 100.0 Dore Editing 5 Select oxgen entry method. Excert fir Excert fir 50 Excert fir	Constituents of Natural Gas	Composition (%)	-		
Bropane (C,H4) 0 Butane (C,H4) 0 Carbon Dioide (CO) 1 Object (CAH) 0 Nitrogen (Na) 1 Total 100.0 Done Editing	Ethane (CH4)	34	-		
Butase (C,Ha) 0 Carbon Dioxide (CO ₂) 1 Orggen (0,) 0 Nitrogen (Na) 1 Total 100.0 Done Editing	Propane (CaHa)	1			
Carbon Dioxide (CDq) 1 Orsgen (0-) 0 Nitrogen (Ny) 1 Total 100.0 Done Editing Select oxgen entry method: Excert Air Total Excess air relative to stolehiometric (2) 50 Reactants Products Products Pressure (atm) 1 1 Species Reactants (1X) Reactants (moles) Products (moles) Products (2) Methane (CH ₄) 6.1 9.40E-01 0.00E-00 0.0 Ethane (CH ₄) 0.1 1000E-02 0.00E-00 0.0 Duran (C+H ₄) 0.1 100E-02 0.00E-00 0.0 Duran (C-H ₄) 0.1 100E-02 0.00E-00 0.0 Duran (C-H ₄) 0.1 100E-02 0.00E-00 0.0 Duran (C-H ₄) 0.0 0.00E-00 0.0 0.0 Duran (C-H ₄) 0.0 0.00E-00 0.0 0.0 Duran (C-H ₄) 0.0 0.00E-00 0.0 0.0	Butane (C ₄ H ₄)	0			
Daggen (0,b) 0 Nitrogen (Na) 1 Total 100,0 Degree netry method:	Carbon Dioxide (CO₂)	1			
Nitrogen (Na) 1 Total 100.0 Done Editing Select ouggen entry method: Image: Constraint of the second of	Oxygen (Oz)	0	_		
Total Done Editing Select oxgen entry method: Excess air relative to stolchiometric (X) 50 Excess air relative to stolchiometric (X) Reactants Products Products (moles) Products (X) Temperature (C) 27 1501 1 1 1 1 Species Reactants (X) Reactants (moles) Products (moles) Products (X) Methane (CH ₄) 6.1 9.40E-01 0.00E-00 0.0 Ethane (CH ₄) 0.1 1006-02 0.00E-00 0.0 Propane (CH ₄) 0.1 1006-02 0.00E-00 0.0 Durane (C-H ₄) 0.0 0.00E-00 0.0 0.0 Carbon dioide (CO ₃) 0.1 100E-02 104E-00 6.4 Nitrogen (N ₄) 74.0 118E-01 13.7 2.00E-00 12.3 Carbon dioide (CO ₃) 0.0 0.00E-00 6.44 0.0 12.3 2.3 Obgen atom (N ₃) 74.0 118E-01 13.8 2.3 2.3 2.3 2.3	Nitrogen (N ₂)	1			
Select orggen entry method: Executars Products Eccess air relative to stolohiometric (2) 50 Temperature (C) 27 150.1 Pressure (atm) 1 1 Species Reactants (2) Products (moles) Products (2) Methane (CH ₁) 6.1 3.40E-01 0.00E-00 0.0 Ethane (C ₂ H ₁) 0.2 3.00E-02 0.00E-00 0.0 Butane (C ₂ H ₁) 0.1 1.00E-02 0.00E-00 0.0 Butane (C ₂ H ₁) 0.0 0.00E-00 0.0 0.0 Carbon diode (CO ₂) 0.1 1.00E-02 0.00E-00 6.7 Orggen (O ₁) 18.7 3.06E-00 3.88E-01 6.4 Nitrogen (N ₂) 7.4.0 1.18E-01 17.3.7 Carbon monside (CO) 0.0 0.00E-00 6.87E-04 0.0 Water (H ₂ O) 0.0 0.00E-00 6.38E-02 0.2 Diggen atom (D) 0.0 0.00E-00 6.38E-03 0.1 Higtoride (OH) 0.0 <td>Total</td> <td>100.0</td> <td>Done Editing</td> <td></td> <td></td>	Total	100.0	Done Editing		
Select oxggen entry method: Excersion Excess air relative to stolchiometric (%) 50 Temperature (C) 27 Fressure (atm) 1 Species Reactants (%) Reactants Products (moles) Pressure (atm) 1 Species Reactants (%) Reactants (moles) Products (moles) Products (C), A 6.1 System (C), H, A 0.1 Operate (C), H, O 0.1 Devane (C), H, O 0.1 Observed 0.00 Butane (C), H, O 0.1 Observed 0.0 Carbon dioxide (CO) 0.1 Observed (C) 0.1 Observed (C) 0.1 Observed (C) 0.3 Nitrogen (Na) 74.0 Title-01 173.7 Carbon monoxide (CO) 0.0 0.00E-00 Vater (H,O) 0.0 0.00E-00 6.7 Nitrogen (Na) 74.0 0.0 0.00E-00 Vater (H,O) 0.0 <th></th> <th></th> <th></th> <th></th> <th></th>					
Overed vagerier ting interfue: Excess air relative to stolchiometric (%) Reactants Products Temperature (C) 27 Pressure (atm) 1 Pressure (atm) 1 Species Reactants (%) Methane (CH ₄) 6.1 9400 0.00E-00 Ethane (CH ₄) 0.1 1 0.00E-00 Oppane (CH ₄) 0.1 1 100E-02 Oppane (CH ₄) 0.1 0.00E-00 0.00 Butane (CA ₁₄) 0.0 0.00E-00 0.00E-00 Carbon dioxide (CO ₃) 0.1 0.00E-00 0.38E-01 6.4 Nitrogen (N ₄) 74.0 118E-01 73.7 Carbon monoide (CO) 0.0 0.00E-00 6.4 Nitrogen (N ₄) 74.0 118E-01 0.00E-00 6.37E-04 0.0 Vater (H ₂ () 0.0 0.00E-00 12.3 Obgen atom (O) 0.00 0.00E-00 <td< td=""><td>Calent owners entry matter d</td><td>Freedow Air</td><td></td><td></td><td></td></td<>	Calent owners entry matter d	Freedow Air			
Excess at reactives Products 150.1 Temperature (C) 27 150.1 Pressure (atm) 1 1 Species Reactants (x) Reactants (moles) Products (moles) Products (x) Methane (CH ₁) 6.1 3.40E-01 0.00E-00 0.0 Ethane (C ₂ H ₁) 0.2 3.00E-02 0.00E-00 0.0 Butane (C ₂ H ₁) 0.1 1.00E-02 0.00E-00 0.0 Butane (C ₂ H ₁) 0.0 0.00E-00 0.0 0.0 Carbon dioide (CO ₂) 0.1 1.00E-02 0.00E-00 6.7 Orggen (O ₂) 18.7 3.06E-00 3.88E-01 6.4 Nitrogen (N ₂) 74.0 1.18E-01 17.37 Carbon monside (CO) 0.0 0.00E-00 6.37E-04 0.0 Water (H ₂ O) 0.0 0.00E-00 6.34E-04 0.0 Usingen atom (D) 0.0 0.00E-00 6.34E-04 0.0 Water (H ₂ O) 0.0 0.00E-00 6.34E-04 0.0	Select oxygen entry method:	EXCOUNT ED			
Reactants Products Temperature (C) 27 180.1 Pressure (am) 1 1 Species Reactants (x) Reactants (moles) Products (moles) Products (x) Methane (CH ₄) 6.1 3.40E-01 0.00E-00 0.0 Ethane (CH ₄) 0.1 100E-02 0.00E-00 0.0 Propane (CH ₄) 0.1 100E-02 0.00E-00 0.0 Carbon dioxide (CO ₄) 0.1 100E-02 104E-00 6.7 Oxygen (O ₄) 13.7 3.05E-00 3.98E-01 6.4 Nitrogen (N ₄) 74.0 1.15E-01 73.7 Carbon monoide (CO) 0.0 0.00E-00 6.37E-04 0.0 Vater (H ₄ O) 0.0 0.00E-00 6.37E-04 0.0 Motogen (N ₄ O)	Excess air relative to stoichiometric [2]	50	1		
Temperature (C) 27 150.1 Pressure (atm) 1 1 Species Reactants (%) Reactants (moles) Products (moles) Products (%) Methane (CH,) 6.1 9.40E-01 0.00E-00 0.0 Ethane (C,H) 0.1 100E-02 0.00E-00 0.0 Propane (C,H) 0.1 100E-02 0.00E-00 0.0 Datane (C,H) 0.1 100E-02 0.00E-00 0.0 Carbon dioxide (CO) 0.1 100E-02 104E-00 6.7 Urgen (D,1) 19.7 3.05E+00 3.98E-01 6.4 Nitrogen (N) 74.0 115E-01 173.7 Carbon monoide (CO) 0.0 0.00E+00 12.3 Disgen atom (0) 0.0 0.00E+00 12.3 Disgen atom (O) 0.0 0.00E+00 13.45E-02 0.2 Hydroside (CH) 0.0 0.00E+00 3.45E-03 0.1 Hydroside (CH) 0.0 0.00E+00 3.45E-03 0.1 H		Reactants	Products		
Pressue (atm) 1 1 Species Reactants (%) Reactants (moles) Products (moles) Products (%) Methane (CH ₁) 6.1 3.40E-01 0.00E-00 0.0 Ethane (C ₄ H ₁) 0.2 3.00E-02 0.00E-00 0.0 Propane (C ₄ H ₁) 0.1 1.00E-02 0.00E-00 0.0 Butane (C ₄ H ₁) 0.0 0.00E-00 0.0 0.0 Butane (C ₄ H ₁) 0.0 0.00E-00 0.0 0.0 Butane (C ₄ H ₁) 0.0 0.00E-00 0.0 0.0 Butane (C ₄ H ₁) 0.0 0.00E-00 0.0 0.0 Butane (C ₄ H ₁) 0.0 0.00E-00 6.7 0 Onggen (O ₄) 18.7 3.06E-00 3.98E-01 6.4 Nitrogen (N ₄) 74.0 1.18E-01 1.18E-01 73.7 Caton monoxide (CO) 0.0 0.00E-00 6.97E-04 0.0 Vater (H ₄ O) 0.0 0.00E-00 3.48E-02 0.2 Diggen atom (O) <td>Temperature (°C)</td> <td>27</td> <td>1510.1</td> <td></td> <td></td>	Temperature (°C)	27	1510.1		
Species Reactants (x) Reactants (moles) Products (moles) Products (x) Methane (CH ₁) 6.1 9.40E-01 0.00E-00 0.0 Ethane (CH ₁) 0.2 3.00E-02 0.00E-00 0.0 Propare (CH ₁) 0.1 1.00E-02 0.00E-00 0.0 Btrane (CH ₁) 0.0 0.00E-00 0.0 0.0 Carbon dioxide (CD ₁) 0.1 1.00E-02 0.00E-00 0.0 Carbon dioxide (CD ₁) 0.1 1.00E-02 0.00E-00 6.7 Oxygen (O ₂) 19.7 3.36E-00 9.38E-01 6.4 Nitrogen (N ₄) 74.0 1.15E-01 115E-01 73.7 Carbon monoxide (CD) 0.0 0.00E-00 2.01E-00 12.3 Okygen atorn (C) 0.0 0.00E-00 3.48E-02 0.2 Water (H ₂ O) 0.0 0.00E-00 3.48E-03 0.1 Nitro totide (NO) 0.0 0.00E-00 8.34E-03 0.1 Hijdroxide (CH) 0.0 0.00E-00 8.3	Pressure (atm)	1	1		
Methane (CH ₁) 6.1 9.40E-01 0.00E-00 0.0 Ethane (CH ₁) 0.2 300E-02 0.00E-00 0.0 Propane (CH ₁) 0.1 100E-02 0.00E-00 0.0 Butane (CH ₁) 0.0 0.00E-00 0.0 0.0 Carbon dioxide (CO ₂) 0.1 100E-02 0.00E-00 0.0 Carbon dioxide (CO ₂) 0.1 100E-02 104E-00 6.7 Disgen (0,1) 19.7 3.05E-00 9.38E-01 6.4 Nitrogen (N ₁) 74.0 115E-01 173.7 Carbon monoxide (CO) 0.0 0.00E-00 6.37E-04 0.0 Vater (H ₂ () 0.0 0.00E-00 2.01E-00 12.3 Disgen atom (0) 0.0 0.00E-00 3.48E-02 0.2 Hydroside (CH) 0.0 0.00E-00 3.48E-03 0.1 Hydroside (CH) 0.0 0.00E-00 3.48E-03 0.1 Hydroside (CH) 0.0 0.00E+00 3.48E-03 0.1 Hy	Species	Reactants (%)	Reactants (moles)	Products (moles)	Products (%)
Ethane (C ₂ H ₁) 0.2 3.00E-02 0.00E-00 0.0 Propane (C ₂ H ₁) 0.1 1.00E-02 0.00E-00 0.0 Butane (C ₂ H ₁) 0.0 0.00E-00 0.00E-00 0.0 Carbon douide (CO ₃) 0.1 1.00E-02 1.04E-00 6.7 Oxygen (0 ₂) 18.7 3.05E-00 3.38E-01 6.4 Nitrogen (V ₂) 74.0 1.15E-01 1.15E-01 7.3.7 Carbon monoxide (CO) 0.0 0.00E-00 6.97E-04 0.0 Vater (H ₂ O) 0.0 0.00E-00 6.97E-04 0.0 Vater (H ₂ O) 0.0 0.00E-00 2.01E-00 12.9 Dinggen atom (O) 0.0 0.00E-00 3.48E-02 0.2 Higdroade (OH) 0.0 0.00E-00 8.34E-03 0.1 Higdroade (OH) 0.0 0.00E-00 8.34E-03 0.1 Higdroade (OH) 0.0 0.00E-00 3.81E-04 0.0	Methane (CH ₄)	6.1	9.40E-01	0.00E+00	0.0
Propane (C,H_i) 0.1 100E-02 0.00E-00 0.0 Butane (C,H_i) 0.0 0.00E-00 0.00E-00 0.0 Carbon dioxide (CD _i) 0.1 100E-02 104E-00 6.7 Duggen (O_i) 19.7 3.05E-00 9.98E-01 6.4 Nitrogen (N ₄) 74.0 115E-01 115E-01 73.7 Carbon monoxide (CD) 0.0 0.00E+00 6.97E-04 0.0 Vater (H ₄ O) 0.0 0.00E+00 2.01E+00 12.3 Obugen atom (O) 0.0 0.00E+00 2.01E+00 12.3 Obugen atom (O) 0.0 0.00E+00 3.48E-02 0.2 Hijdroside (CH) 0.0 0.00E+00 8.34E-03 0.1 Hijdroside (CH) 0.0 0.00E+00 8.34E-03 0.1 Hijdroside (CH) 0.0 0.00E+00 2.31E-05 0.0 Hijdroside (CH) 0.0 0.00E+00 3.31E-04 0.0	Ethane (C ₂ H ₆)	0.2	3.00E-02	0.00E+00	0.0
Butane (C,H) 0.0 0.00E+00 0.00E+00 0.00 Carbon dioxide (CO) 0.1 1.00E+02 1.04E+00 6.7 Draygen (O) 187.7 3.05E+00 3.98E+01 6.4 Nitrogen (Na) 74.0 1.15E+01 1.15E+01 73.7 Carbon monoide (CO) 0.0 0.00E+00 6.87E+04 0.0 Vater (H_CO) 0.0 0.00E+00 2.01E+00 12.3 Draygen atom (O) 0.0 0.00E+00 3.48E+02 0.2 Hydrogen (OPI) 0.0 0.00E+00 8.34E+03 0.1 Hydrogen (H) 0.0 0.00E+00 2.31E+05 0.0 Hydrogen (H_1) 0.0 0.00E+00 3.48E+03 0.1 Hydrogen (H_1) 0.0 0.00E+00 3.48E+03 0.1	Propane (C ₁ H ₁)	0.1	1.00E-02	0.00E+00	0.0
Carbon dioxide (CO ₄) 0.1 100E-02 104E-00 6.7 Davgen (O ₄) 19.7 3.05E-00 3.98E-01 6.4 Nitrogen (N ₄) 74.0 1.15E-01 1.15E-01 73.7 Carbon monoxide (CO) 0.0 0.00E-00 6.97E-04 0.0 Vater (H ₄ O) 0.0 0.00E-00 2.01E-00 12.9 Diagen atom (O) 0.0 0.00E-00 3.48E-02 0.2 Higticoside (OH) 0.0 0.00E-00 8.34E-03 0.1 Higdrogen atom (H) 0.0 0.00E-00 2.31E-05 0.0 Higdrogen (H ₁) 0.0 0.00E-00 3.31E-04 0.0	Butane (C ₄ H ₄₁)	0.0	0.00E+00	0.00E+00	0.0
Outgoen (0,1) 19,7 305E-00 9,98E-01 6.4 Nitrogen (Na) 74.0 115E-01 115E-01 73,7 Cathon monoxide (CO) 0.0 0.00E+00 6.97E-04 0.0 Vater (H ₄ O) 0.0 0.00E+00 2.01E+00 12.3 Obugen storm (C) 0.0 0.00E+00 2.01E+00 12.3 Obugen storm (C) 0.0 0.00E+00 3.48E+02 0.2 Hijdroside (CH) 0.0 0.00E+00 8.34E+03 0.1 Hijdroside (CH) 0.0 0.00E+00 2.31E+05 0.0 Hijdrosien (H) 0.0 0.00E+00 3.81E+03 0.1 Hijdrosien (H) 0.0 0.00E+00 3.81E+04 0.0	Carbon dioxide (CO ₂)	0.1	1.00E-02	1.04E+00	6.7
Number Number Number Number Number Number Number 74.0 115E-01 115E-01 73.7 Carbon monoxide (CD) 0.0 0.00E-00 6.97E-04 0.0 Water (H-0) 0.0 0.00E-00 2.91E-00 12.9 Daygen atom (D) 0.0 0.00E-00 4.94E-04 0.0 Nitric Oxide (ND) 0.0 0.00E-00 3.48E-02 0.2 Hydrogen (CH) 0.0 0.00E-00 8.34E-03 0.1 Hydrogen (CH) 0.0 0.00E-00 2.3E-05 0.0 Hydrogen (H) 0.0 0.00E-00 3.8E-04 0.0	Oxugen (O ₁)	19.7	3.05E+00	9.98E-01	64
Carbon monoide (CD) 100 1000E-00 6.37E-04 0.0 Vater (HyC) 0.0 0.00E-00 6.37E-04 0.0 Vater (HyC) 0.0 0.00E-00 2.01E-00 12.9 Objgen atom (O) 0.0 0.00E-00 4.04E-04 0.0 Nitric Daide (ND) 0.0 0.00E-00 3.48E-02 0.2 Hydrogen atom (H) 0.0 0.00E-00 8.34E-03 0.1 Hydrogen atom (H) 0.0 0.00E-00 2.31E-05 0.0 Hydrogen (Hy) 0.0 0.00E-00 3.81E-04 0.0	Nitrogen (N-)	74.0	115E+01	115E+01	73.7
Vater (H ₂ C) 0.0 0.00E+00 2.01E+00 12.3 Obgen atom (C) 0.0 0.00E+00 4.04E;04 0.0 Nitro Oxide (NO) 0.0 0.00E+00 3.49E;02 0.2 Hydrogen atom (H) 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 ₁) 0.0 0.00E+00 3.81E;04 0.0 Calculate Reset Help 1	Carbon monoside (CO)	0.0	0.00E+00	6.97E-04	0.0
Osuge atom (O) 0.0 0.00E-00 4.04E-04 0.0 Nitro Colide (NO) 0.0 0.00E-00 3.49E-02 0.2 Hijdroside (OH) 0.0 0.00E-00 8.34E-03 0.1 Hijdrogen atom (H) 0.0 0.00E-00 2.31E-05 0.0 Hijdrogen (H ₂) 0.0 0.00E-00 2.31E-05 0.0 Calculate Reset Help	Vater (H ₂ O)	0.0	0.00E+00	2.01E+00	12.9
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 Hydroxide (OH) 0.0 0.00E+00 2.31E+05 0.0 Hydrogen (H1) 0.0 0.00E+00 3.81E+04 0.0 Hydrogen (H2) 0.0 0.00E+00 3.81E+04 0.0	Oxygen atom (O)	0.0	0.00E+00	4.04E-04	0.0
Hydroside (DH) 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 ₁) 0.0 0.00E+00 3.61E-04 0.0 Hydrogen (H ₁) 0.0 0.00E+00 3.61E-04 0.0	Nitric Oxide (NO)	0.0	0.00E+00	3.49E-02	0.2
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	Hydroxide (OH)	0.0	0.00E+00	8.34E-03	0.1
Hydrogen (Hz) 0.0 0.00E+00 3.61E-04 0.0 Calculate Reset Help	Hydrogen atom (H)	0.0	0.00E+00	2.31E-05	0.0
Calculate Reset Help	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: CO₂, O₂, O, CO, H₂O, N₂, NO, OH, H, H₂

• 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

Flame Temperature	1510.1	°C			
utside Surface Temperature	828.7	°C	Casting Speed	4	ton/minute
Nozzle Orifice Area	4.42E-01	inch ²	Density of Steel	7015	kg/m ³
Characteristic diameter	0.0732	m	Thermal Conductivity of Steel	33	W/(m-k)
Gas Pressure	9	PSI	Dynamic Viscosity of Steel	0.0055	Ns/m ²
Friction Factor	0.03	m/m	Thermal Diffusivity	6.10E-06	m²/s
Gas Pressure	6.21E+04	Pa	Casting Speed	2.26	m ³ /s
Nozzle Orifice Area	2.85E-04	m ²	Reynolds Number	2.11E+05	
Gas Density	1.45E-01	kg/m ³	Prandtl Number	1.29E-01	
Velocity	9.24E+02	m/s	b	7.96E-01	
Mass flow Rate	3.83E-02	kg/s	а	8.22E-01	
Free Convection	7.64	W/m²-K	Nusselt Number	7.45E+01	
Forced Convection	72.45	W/m ² -K	Heat Transfer Coefficient	33594.11	W/m ² -K
			$Re = \frac{2ur}{v}$ $b = \frac{1}{3} + 0.5 Exp(-0.6 * Pr)$	$Pr = \frac{v}{\alpha}$ $a = 0.88 - \frac{v}{\alpha}$	$\frac{0.24}{4+Pr}$
			$Nu = 5 + 0.015 Re^a Pr^b$	$h = \frac{Nu.k}{2r}$	
ity of Illinois at Urbana-Ch	ampaign		Metals Processing Simulation Lab	Varun Kur	nar Singh •



Heat Transfer Coefficients

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

$$N u_{avg} = \left\{ 0.825 + \frac{\left[0.387 R a^{1/6}\right]}{\left[1 + \left(\frac{0.429}{P r}\right)^{9/16}\right]^{8/27}} \right\}$$

• Forced Convection from flame: The Petukhov, Kirillov, and Popov [1] is used

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

- The forced heat transfer coefficient was calculated to be 72.5 W/m²K.
- The free heat transfer coefficient was calculated to be 7.6 W/m²K
- 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]: $\lambda = \sum_{i=1}^{n} \frac{y_i \lambda_i}{y_i \lambda_i}$

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

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

$$A_{ij} = \frac{\left[1 + (\eta_{i} / \eta_{j})^{1/2} (M_{j} / M_{i})^{1/4}\right]^{2}}{\left[8 (1 + M_{i} / M_{j})^{1/2}\right]^{1/2}}$$
$$A_{ji} = \frac{\eta_{j}}{\eta_{i}} \frac{M_{i}}{M_{j}} A_{ij}$$

Metals Processing Simulation Lab

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

And M_{i} , M_{i} are the molecular weights of pure i and j

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

```
University of Illinois at Urbana-Champaign
```

Heat Transfer Model for the refractory – Main Page

Heat Transfer Model of skull clogging for variable layers

Geometry of Nozzle				Cle	ar
Outer Radius of Refractory	78	mm			<u> </u>
Enter Number of layers	3			A : D	C 1
Emmissivity	0.5			Assign R	efractory
				Рторе	rties
Preheat					
Ambient Temperature	24.0	°C			
Initial Nozzle Temperature	9.0	°C			
FlameTemperature	1510.0	°C			
Internal heat transfer Coefficient (forced)	72.5	W/(m ² K)			
External heat transfer Coefficient (free)	7.64	W/(m ² K)		Preheat S	Simulation
Preheat Time	120.0	min.			
Time Step	0.01	S		View Prel	heat Plots
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)	24.0	°C			
Ambient Temperature (Inside)	24.0	°C			
Internal heat transfer Coefficient	7.64	W/(m ² K)		Cooldown	Simulation
External heat transfer Coefficient	7.64	W/(m ² K)			
Cooldown Time	15.0	min.			1
Time Step	0.01	S		View Cooldown Plots	
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

Varun Kumar Singh



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.





University of Illinois at Urbana-Champaign

Metals Processing Simulation Lab

Varun Kumar Singh

.

• 14





Steel Shell Solidification Model

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

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

Top row temperatures:

$$T_i = T_{pour}$$

Top row enthalpies [2]:

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

where $L_{\rm f}$ is the latent heat of fusion.

16

.



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: •

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

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

$$T_{i} = \min\left[\frac{H_{i}}{C_{p}}, \max\left\{\frac{H_{i} - L_{f}}{C_{p}}, T_{sol}\right\}\right]$$

Metals Processing Simulation Lab

nuous asting nsortium

University of Illinois at Urbana-Champaign

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]:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) = 0 \qquad T_{\text{flame}} \qquad r \qquad r$$
Heat flux through the nozzle is calculated using: h_{flame}, T_1

$$q = \frac{T_{\text{flame}} - T_{\text{ambient}}}{\frac{1}{h_{\text{flame}}r_i} + \frac{\ln(r_o/r_i)}{k} + \frac{1}{h_{\text{ambient}}r_o}} \qquad r_i \qquad \text{Refractory, k} \quad r_o \qquad h_{\text{ambient}}, T_2 \qquad T, r \qquad T_{\text{ambient}}, T_2$$
Finally, the temperatures in the nozzle are :
$$r_i = r_o - t$$

$$T_1 = T_{\text{flame}} - \frac{q}{h_{\text{flame}}r_i} \qquad T = T_1 - \frac{q}{k} \ln\left(\frac{r}{r_i}\right)$$

University of Illinois at Urbana-Champaign

.

18

.

Varun Kumar Singh

.



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/(m²K)
External Convection heat transfer Coefficient (Free)	h _{ambient}	7.3	W/(m ² K)
Thermal Conductivity	К	18.21	W/m-K
Specific Heat	Cp	804*	J/kg-K
Density	ρ	2347	kg/m³
Stefan Boltzman's Constant	σ	5.67E-8	
Emmissivity	3	0.96	

* Parameters required by transient simulation method





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.

Metals Processing Simulation Lab

luous

ortium

University of Illinois at Urbana-Champaign

Simulation Parameters – Validation of transient aspect of the model

Varun Kumar Singh

21

	i		
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	к	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	3	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







.

•

Comparison with measurements (inside heat transfer coefficient = 72 W/m²-K)



Comparison with measurements (inside heat transfer coefficient = 18 W/m²-K, emissivity = 0.5)



asting



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
University of Illinois at Urbana-Champaign	Metals Processing Simulation Lab	Varun Kumar Singh • 27



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/m²-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.



- 1. Incropera, F.P., and Dewitt, P.D., 2002, *Fundamentals of Heat and Mass Transfer,* John Wiley and Sons, New York.
- 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.
- 5. Report on "Modeling of Tundish Nozzle Preheating" by J. Mareno and B.G. Thomas.

Metals Processing Simulation Lab



University of Illinois at Urbana-Champaign

Acknowledgements

Varun Kumar Singh

- Continuous Casting Consortium Members (ABB, Arcelor-Mittal, Baosteel, Corus, LWB Refractories, Nucor Steel, Nippon Steel, Postech, Posco, ANSYS-Fluent)
- Rob Nunnington, LWB Refractories