Introduction to Furnace Thermodynamics

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Goals and Motivation

- **Intimate Knowledge**
  - Better understanding will give more efficient results

- **Goals**
  - Develop a computational model of an iron melting furnace
  - Create an optimization program in accessible software

- **Alternative Fueled Furnace**
  - Coke becoming a limited resources
  - Safer fuels than coke
Process

- Charge material
  - Pieces of iron and limestone
  - Coke
- Stack
  - Section above the Tuyeres
- Tuyeres
  - Ports into the furnace for air and viewing
- Bed
  - Section below the tuyeres
Fundamentals of Thermodynamics

- Thermodynamics: The study of energy displacement with respect to work and heat that incorporates physics, chemistry and engineering.

- 1\textsuperscript{st} Law: Energy Balance
  - A specific amount of matter undergoing any process experiences a change in energy equal to the amount of energy transferred to it.
Energy

- Energy (NRG)
  - Ability of a system to do work on other systems
  - Kinetic NRG: Motion  \[ \Delta KE = \frac{1}{2} m v_f^2 - v_i^2 \]
  - Potential NRG: Gravity \[ \Delta PE = mg(z_2 - z_1) \]
  - Internal NRG: Stored \[ \Delta U = U_2 - U_1 \]
    - Compressed Springs
    - Chemical Reactions
  - Work: External displacement of environment (W)
    - Moving parts
  - Heat: Energy based on temperature change. (Q)
  - Overall NRG equation
    \[ \Delta KE + \Delta PE + \Delta U = Q - W \]
Internal NRG

- **Enthalpy**
  - The sum of internal energy along with the energy made by the displacement of the products

\[ H = U + pV \]

- **Combustion**
  - Rapid chemical reaction in which combustibles are oxidized resulting in the release of energy and the formation of products.

\[ \text{fuel} + \text{oxidizer} \rightarrow \text{products} \]

NRG in the form of heat
Internal Energy

- **Enthalpy of Formation**
  - NRG released or absorbed from the creation of compounds during a chemical reaction at a given temperature and pressure.
  - Expressed in NRG / Mol

- **CO₂**: $-169,300 \ \frac{Btu}{lbmol} \quad -393,520 \ \frac{kJ}{kmol}$

- **C₃H₈**: $-44,680 \ \frac{Btu}{lbmol} \quad -103,850 \ \frac{kJ}{kmol}$

- **Mol**
  - Used in chemistry to express amounts of a chemical substance
Melting Iron

• Specific Heat
  • Amount of energy per mass required to raise the temperature of a given body
  • Different for every substance

\[ Q = mc\Delta T \]

NRG in the form of heat  \( \rightarrow \)  Mass  \( \rightarrow \)  Specific Heat  \( \rightarrow \)  Change in Temperature

• Specific Heat of cast iron:

\[ 0.11 \frac{Btu}{lbF^\circ} \quad \text{and} \quad 0.46 \frac{kJ}{kgK} \]
Melting Iron

- Example:
  - Heat 50 lbs of iron to 2900 °F, how much coke is needed?
- Free Body Diagram
Melting Iron

• Assumptions
  • Ignore potential and kinetic NRG
  • Air is feed into the furnace which is oxygen and nitrogen, nitrogen is inert and combustion is complete
  • The combusting air and products form ideal gases
  • Only concerned with the melt zone
  • All energy is absorbed by the iron
  • No external work is being done

• Reduced energy equation

\[ \Delta KE + \Delta PE + \Delta U = Q - W \]

Q: NRG from heat
W: NRG from external work
\( \Delta KE \): Kinetic NRG
\( \Delta PE \): Potential NRG
\( \Delta U \): Internal NRG
Melting Iron

- Analysis

- Use specific heat to determine rough estimate for NRG required to melt iron

\[ \Delta U = Q \]

\[ Q = mc\Delta T \]

\[ Q = (50lb) \cdot (0.11 \frac{Btu}{lbF^o}) \cdot (2900 - 60)F^o \]

\[ Q = 15,890 Btu \]

Q: NRG from heat
N: mols from combustion
h: Enthalpy of Formation
c: Specific heat
m: mass
Melting Iron

- Analysis Cont.
  - Use enthalpy of formation to determine amount of reactants needed
  - At standard temperature and pressure
  - Equal concentrations

\[ \text{C} + \text{O}_2 \rightarrow \text{CO}_2 \]

\[ \Delta U = n_{\text{CO}_2} \bar{h}_{\text{CO}_2} - n_{\text{C}} \bar{h}_{\text{C}} - n_{\text{O}_2} \bar{h}_{\text{O}_2} \]

\[ \Delta U = Q \]

\[ Q_{\text{combustion}} = n_{\text{CO}_2} \bar{h}_{\text{CO}_2} - n_{\text{C}} \bar{h}_{\text{C}} - n_{\text{O}_2} \bar{h}_{\text{O}_2} \]

\[ \bar{h}_{\text{O}_2} = \bar{h}_{\text{C}} = 0 \]

\[ n_{\text{C}} = n_{\text{O}_2} = n_{\text{CO}_2} \]

\[ Q_{\text{combustion}} = n_{\text{C}} \bar{h}_{\text{CO}_2} \]

Q: NRG from heat
N: mols from combustion
h: Enthalpy of Formation
Melting Iron

- Analysis Cont.

\[
\frac{Q}{h_{\text{co}_2}} = n_c
\]

\[
\frac{15,890 \text{ Btu}}{169,300 \frac{\text{Btu}}{\text{lbmol}}} = n_c
\]

\[0.094 \text{ lbmol} = n_c\]

\[M_c = 12.01 \frac{\text{lb}}{\text{lbmol}}\]

\[m_c = M_c \cdot n_c \cdot \left(\frac{1}{0.85}\right)\]

\[m = 1.32 \text{ lb}\]

Q: NRG from heat
N: mols from combustion
h: Enthalpy of Formation
M: Molar mass
m: mass
Melting Iron

- Change original assumption
  - Only 25% of combustion goes into melting iron

\[
\frac{15,890 \text{ Btu}}{(0.25) \cdot 169,300 \text{ Btu/lbmol}} = n_c
\]

\[0.375 \text{ lbmol} = n_c\]

\[
m_c = M_c \cdot n_c \cdot \left(\frac{1}{0.85}\right)
\]

\[M_c = 12.01 \text{ lb/lbmol}\]

\[m = 5.3 \text{ lb}\]

- Still wrong?
  - The reaction does not take place at standard temperature and pressure
  - Does not take into account preheating of iron
  - NRG lose from air and the environment
Computational Models

- Solves governing equations
  - Momentum – Air flow through the furnace
  - Mass transfer – Coke being consumed
  - Energy – Temperature field
- Assumptions
  - Iron is melted predominantly through convection
- Matlab
  - High-level language for algorithm development
  - Finite difference method
    - A numerical method to approximate the solution to differential equations
\[
\frac{\partial \omega}{\partial t} = -V_x \frac{\partial w}{\partial x} - V_y \frac{\partial w}{\partial y} + \nu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \right) - \frac{1}{\rho_g} \left( \frac{150 \mu (1 - \varepsilon)^2 D_f \partial \omega}{\varepsilon^3 d_c^2} + \frac{1.75 \rho_g (1 - \varepsilon) D_f |V| \cdot \partial \omega}{\varepsilon^3 d_c} \right)
\]

\[
\frac{\partial C}{\partial t} = -V_x \frac{\partial C}{\partial x} - V_y \frac{\partial C}{\partial y} + D_{eff} \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) - KC
\]

\[
\frac{\partial T}{\partial t} = -V_x \frac{\partial T}{\partial x} - V_y \frac{\partial T}{\partial y} + \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \dot{Q}
\]
Matlab

Combustion

- Assumes only a carbon-oxygen reaction,
- Reaction happens very fast at the surface of coke particle
- Reaction rate constant effected by:
  - Temperature
  - Air velocity
  - Porosity of coke
  - Size of coke

\[
C_{\text{coke}} + O_2 \xrightarrow{\text{yields}} CO_2
\]

\[
D_e \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial \tilde{C}_A}{\partial r} \right) - r_v \rho_p = \frac{\partial}{\partial \theta} (\varepsilon_p \tilde{C}_A)
\]

\[
r_v = -K \tilde{C}_A
\]

\[
K = \frac{1 - \varepsilon}{\frac{1}{k_x E_f} + \frac{d_c}{6k_f}}
\]

- $D_e$ = Diffusivity
- $\varepsilon$ = Void fraction
- $k_x$ = Mass transfer coefficient
- $k_f$ = Rate constant
- $E_f$ = Catalyst Effectives Factor
- $d_c$ = Diameter of coke particle
- $r$ = Radius inside the catalyst
- $r_v$ = Overall reaction rate
- $\tilde{C}_A$ = Concentration of fluid reactant
- $\rho_p$ = Density of catalyst particle
- $\frac{\partial}{\partial \theta} (\varepsilon_p \tilde{C}_A)$ = Transient Term
Matlab

- **Energy equation**
  - Energy released in carbon-oxygen reaction
  - Energy gained from heat of formation
    - Amount of products equals amount of reactants
    - Assumes Reaction is at STP, leaving only carbon dioxide
  - Oxygen becomes limiting factor

\[
0 = \dot{Q}_{\text{combustion}} + \dot{n}_C \bar{h}_C + \dot{n}_{O_2} \bar{h}_{O_2} - \dot{n}_{CO_2} \bar{h}_{CO_2} \\
\dot{n}_C = \dot{n}_{O_2} = \dot{n}_{CO_2} \\
\dot{Q}_{\text{combustion}} = \dot{n}_{CO_2} (\bar{h}_{CO_2}) \\
KC_A = \dot{n}_{CO_2} \\
\dot{Q}_{\text{combustion}} = \frac{1 - \varepsilon}{k_x E_f} + \frac{d_e}{6k_f} (\bar{h}_{CO_2})C_{O_2}
\]

\[\bar{h} = \text{Enthalpy of formation}\]

\[\dot{n} = \text{Molar flow rate}\]

\[\text{C}_{\text{coke}} + O_2 \xrightarrow{\text{yields}} CO_2\]
Energy generation term
- Fraction of heat is absorbed by fluid, \( \beta \)
- Uses an overall heat transfer coefficient between fluid and solid

Heat Equation is effected by:
- Oxygen Concentration
- Reaction rate

\[
\dot{Q} = \beta \dot{Q}_{\text{Combustion}} - h_o (T_g - T_s)
\]

\[
\frac{\partial T}{\partial t} = -V_x \frac{dT}{dx} - V_y \frac{dT}{dy} + \alpha \left( \frac{d^2 T}{dx^2} + \frac{d^2 T}{dy^2} \right) + \dot{Q}
\]

\[
h_o = \text{Effective heat transfer coefficient}
\]

\[
h = \text{Heat transfer coefficient}
\]
Cupollette Model

- Parameters from existing cupollette
- Xena, Binghamton’s larger iron furnace
- Same as Mothra
- Grid spacing: 0.5 cm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Height</td>
<td>0.605 m</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.36 m</td>
</tr>
<tr>
<td>Bed Height</td>
<td>0.18 m</td>
</tr>
<tr>
<td>Tuyere Diameter</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Lid Diameter</td>
<td>0.11 m</td>
</tr>
<tr>
<td>Blast Temp.</td>
<td>289 K</td>
</tr>
<tr>
<td>Blast Rate (O₂)</td>
<td>0.224 kg/s</td>
</tr>
</tbody>
</table>
Cupollette Model

Stream Function

Velocity Magnitude cm/s

\( x \text{ (cm), Diameter: 36} \)

\( y \text{ (cm), Height: 60.5} \)
Cupollette Model

Oxygen Concentration
Cupollette Model

Temperature in Degrees Kelvin

Temperature of Melt Zone Degrees Kelvin
Alternative Fuels

- **Propane**
  - Not as high NRG content
  - Clean burning
  - Expensive but easily obtainable

- **Oil**
  - Inexpensive and easily obtainable
  - Dirty oil poses problems

- **Electric**
  - High initial Expense
  - Higher maintenance

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Unit</th>
<th>Energy Content (Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>1 Kilowatt-hour</td>
<td>3412</td>
</tr>
<tr>
<td>Coke</td>
<td>1 pound</td>
<td>12500</td>
</tr>
<tr>
<td>Crude Oil</td>
<td>1 Barrel - 42 gallons</td>
<td>5800000</td>
</tr>
<tr>
<td>Fuel Oil no.2</td>
<td>1 Gallon</td>
<td>139600</td>
</tr>
<tr>
<td>Fuel Oil no.4</td>
<td>1 Gallon</td>
<td>145100</td>
</tr>
<tr>
<td>Fuel Oil no.5</td>
<td>1 Gallon</td>
<td>148800</td>
</tr>
<tr>
<td>Fuel Oil no.6</td>
<td>1 Gallon</td>
<td>152400</td>
</tr>
<tr>
<td>Diesel Fuel</td>
<td>1 Gallon</td>
<td>139000</td>
</tr>
<tr>
<td>Gasoline</td>
<td>1 Gallon</td>
<td>124000</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>1 Cubic Foot</td>
<td>950 - 1150</td>
</tr>
<tr>
<td>Heating Oil</td>
<td>1 Gallon</td>
<td>139000</td>
</tr>
<tr>
<td>Kerosene</td>
<td>1 Gallon</td>
<td>135000</td>
</tr>
<tr>
<td>Propane</td>
<td>1 Gallon</td>
<td>91330</td>
</tr>
<tr>
<td>Propane</td>
<td>1 Cubic Foot</td>
<td>2550</td>
</tr>
<tr>
<td>Wood - air dried</td>
<td>1 pound</td>
<td>8000</td>
</tr>
</tbody>
</table>

http://www.engineeringtoolbox.com
Alternative Designs

- Open Hearth Furnace
  - Predominantly used in steel manufacturing
  - Gas-Air mixture
  - Regenerative firing
  - Time consuming
Alternative Designs

- **Electric Arc Furnace**
  - Large amounts of current and voltage passing through electrodes
  - Electric arc between electrodes provide heat
  - Electrodes are slowly used
Alternative Designs

- Oil / Propane Fired Furnace
  - Similar construction to a cupola
  - Uses a false bed or continuous feed
  - Packing material made of ceramics
Conclusion

- Computational model
  - Good start for a simple program

- Alternative Fuels
  - Pros and Cons

- Future work
  - Write optimization program in accessible software (ex. Excel, Wolfram Alpha widget)
  - Experiment with multiple furnace designs for batch melting
Thank you

Ken Payne
Elena Lourenco
Vaughn Randall
Roy McGrann
Bruce Murray
References


9. http://hyperphysics.phy-astr.gsu.edu