Combination of CFD Results with Empirical Techniques to Predict Long-Term Boiler Operational Characteristics

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Overview

- What is a SRU?
- WHB overview
- Known modes of failure of WHBs
- Current condition analyzed
- Process CFD modeling
- Extrapolating results to long-term operation – including fouling
- DNB modeling
- Development of limit curves
What is an SRU?

- Sulfur recovery units (SRUs) are used to recover elemental sulfur from gas streams containing $H_2S$
- Consist of: Thermal reactor, waste heat boiler (WHB), primary and secondary condensers

\[
\begin{align*}
H_2S + \frac{3}{2}O_2 & \rightarrow SO_2 + H_2O \\
2H_2S + SO_2 & \rightarrow \frac{3}{2}S_2 + 2H_2O
\end{align*}
\]
What is an SRU?

- Gas is reacted sub-stoichiometrically
- Reaction is exothermic with firing temperatures between 2200 and 2800 °F
- Reaction does not complete typically 3-5 %Mol H₂S remaining
- Gas enters WHB to be cooled w/ byproduct of plant steam (500 – 650 psig)
- Cooled gas enters the condensers for extraction of elemental sulfur
WHB Overview

- Fired tube boiler – typically 2 pass
- Gas enters from thermal reactor through ferrule lined tubesheet
- Exits through cross-over to condenser
Known Modes of Failure for WHBs

- Over-temperature – Firing temperature exceeds 3000 °F refractory damage can occur
- Sulfidation corrosion – long-term
- Departure from nucleate boiling (DNB) – short-term
Known Modes of Failure for WHBs - Sulfidation

![Graph showing the relationship between temperature and mol% of H2S for different sulfidation rates.](image1.png)

![Image of corroded metal surface.](image2.png)

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Known Modes of Failure for WHBs - DNB

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Current Condition Analyzed

- WHB replaced in-kind in 2000
- Eddy current inspection in 2009 indicated significant tube loss – retubing required
- Inspection of shell side indicated significant fouling – hard and soft scale
- Determine why corrosion had occurred
- Mitigate future corrosion
- Develop operational limit curves
Process Side CFD Modeling

- Develop process side model to determine peak flux / temperature downstream from ferrule
- Determine cases for analysis from distributed control system (DCS) data
- Extrapolate process side analyses to operational history of WHB
Process Side CFD Modeling
Process Side CFD Modeling

- Determination of cases for analysis
  - Acid gas flow rate
  - Acid gas composition
  - Feed Rate x Inlet Temperature (pseudo-duty)
  - $O_2$ Concentration

- DCS indicated 4 process points of interest
  - Average air only
  - Maximum air only
  - Low CO$_2$ case
  - Maximum $O_2$ enrichment
  - Also run 10% greater than max $O_2$
Process Side CFD Modeling

- New Ferrule Design 1
- New Ferrule Design 2
- Original Ferrule
- Linear (New Ferrule Design 2)
- Linear (Original Ferrule)

Peak Flux (BTU/ft²) vs. Mdot*Temperature
Process Side CFD Modeling

![Graph showing peak temperature versus peak flux with a linear trend line.]

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Extrapolating Results to Long-Term Operation

- Couple curve-fits with historical DCS data in MatLab
Long-Term Operation - Fouling

- Fouling growth typically modeled by fouling growth equation

\[ m(t) = \frac{k \rho}{\lambda} \left( t \lambda_c + \frac{\lambda_r}{\lambda} \left( 1 - e^{-\lambda t} \right) \right) \]
Long-Term Operation - Fouling

- Assume fouling distributes evenly over outside of tube, therefore $r_{i+1} \sim m(t)^{0.5}$
  \[ R_{\text{cond}} = \frac{\ln(r_{i+1} - r_i)}{2\pi k_i} \]

- Convective resistance is known to be:
  \[ R_{\text{conv}} = \frac{1}{h_o 2\pi r_o} \]

- Determine new external convection coefficient:
  \[ h_{\text{new}} = \frac{1}{2\pi r_{i+1}(R_{\text{cond}} + R_{\text{conv}})} \]
Long-Term Operation - Fouling

- Combine fouling mass growth with new external convection coefficient:
Long-Term Operation - Fouling

- Use periodic models to relate external convection coefficient to internal temp.
Long-Term Operation - Fouling

- Determine temperature multiplier versus time:

![Graph showing temperature multiplier versus time with different conditions](image-url)
Long-Term Operation - Fouling

- Experiment with possible fouling regimes:
DNB Modeling

- Determine how close current process is to initiating a DNB event
- Transient VOF model with boiling required
- Used to determine margin of safety (MOS)
- Model can be modified through field functions to account for DNB event (ASME PVP2009-78073)
DNB Modeling

- 24 million cell model of first pass
- Transfer process fluxes using X, Y, Z table data
High buoyancy induced velocities minimize WHB propensity for DNB
Developing Operational Limit Curves

- Must rely on measurable plant process data: mass flow rate and firing temperature
- 3 regimes must be considered
  - Refractory over-temperature
  - Long-term sulfidation corrosion
  - Short-term DNB events
- Combine results of analyses to develop curve
Developing Operational Limit Curves

- Refractory Temperature Limited
- Tube Tip Temperature Limited

Temperature (F) vs. Mass Flow (lb/hr)

- FOC Flux Limiting Case
- Tube Temperature Limited Case

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Conclusions

- Results of process side CFD models were used to predict the historical operation of a WHB – Full transient too time consuming
- Predicted fouling growth was long-term – Recommendations on future WHB operation
- Predicted MOS to DNB, used to develop short-term limit curve
Further Information