Furnace Performance and Runlength Improvement Through Multi-Model Techniques

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Furnace Performance Improvement Impact

The ultimate arbiter for Furnace Performance improvement is improved ethylene production and reduced cost to maintain and operate the furnaces

- Ethylene production increase
  - Furnace throughput increase
  - Furnace yield improvement
  - Furnace Run length improvement (increased uptime/availability)

- Cost reduction
  - Energy utilization efficiency and recovery efficiency
  - Decoke costs
  - Effective cost based on tube replacement frequency
  - Effective cost based on unforeseen shutdown frequency
  - Maintenance costs
Typical Cracking Furnace Performance Considerations

Ethylene plants tend to have common furnace section issues, which when addressed provide the necessary improvement

• Reduced furnace run lengths are often a problem triggered by
  ✓ Tube Metal Temperatures being too high
    ▪ Coking / decoking issues
    ▪ Channeling
    ▪ Flame impingement
  ✓ Coil Pressure Ratio being too high from coking
    ▪ Feed imbalance
  ✓ TLE limitations

• Need for calculated adjustments of heat flux and/or dilution steam to optimize cracking severity versus run length instead of fixed settings
  ✓ Adjustments in coil level-wise heat flux by monitoring coking rate helps in reducing differential coking and abnormal CIP/TMT rise
  ✓ Differential coking if arrested properly helps in max. severity and gains
  ✓ Increasing the dilution steam flow to certain level of SHC ratio helps in improving yields and reducing coking rate, however maintaining optimum ratio is critical as higher SHC ratio increases firing and CIP

• Need for proper feed and heat flux balancing based on identification of abnormal deviations and faulty indications

Abbreviations:
CIP: Coil Inlet Pressure, TMT: Tube Metal Temperature, SHC: Steam to Hydrocarbon
Furnace Performance Improvement Using Analytics

Furnace performance and hence plant profitability has been substantially improved safely by micro tracking and multi dimensional analytics of furnace data

• Process analytics → impacts *throughput, availability, yield and efficiency*
  ✓ Simulation/modeling
  ✓ Data Analytics
  ✓ Dashboards
  ✓ DMAIC Process for implementation

• Equipment Focused analytics → impacts *availability and performance*
  ✓ Predictability: maintenance, functional life profile
  ✓ Operational status within optimal boundary conditions

• Safety/Environmental analytics → *Prevention of accidents / spills / non-compliance*
  ✓ Information availability and access
  ✓ Real-time status
  ✓ Predictability of problems
Cracking Performance Improvement Methodology
We know of consistent cracking furnace performance improvement at over 15 ethylene sites using multi-model based analysis and tracking methodology, followed by Ingenero.
Models At The Core Of Ethylene Plant Analytics

Different types of models form an essential part of the process, equipment and compliance analytics

Fundamental first principle Yield models *(reaction kinetics, mass & heat transfer, thermodynamics)*

- COILSIM1D

Steady state process simulation & optimization
- Aspen suite, Hysys, PRO II, FRNC, HTFS, HTRI

Computational Fluid Dynamics (CFD)
- Fluent, OpenFOAM

Data driven models
- Statistical, neural net, pattern recognition, Weibull analysis, PCA, PLS, time series

LP models
- Integrated supply chain model (supply, production, inventory, distribution), strategic planning models, scheduling models, Optimal feed distribution

Dynamic models
- Operator training, model predictive control

Abbreviations:
PCA: Principle Component Analysis, PLS: Partial Least Squares
Appropriate Technology Utilization
Use of appropriate models and technology is key to help the plant to maximize profits/production and extend furnace run lengths

- Reaction kinetics model to compute yield as a function of key parameters like Feed type, SHC, COT, COP
- Convection section modeling (e.g. FRNC 5, HTRI Fired Heaters) to achieve maximum throughput / cracking safely
- Fire box modeling (geometry / heat flux) to control rate of fouling at the individual coil level
- CFD to address flue gas channeling, flame impingement and hot spots on tubes
- Data driven models allow appropriate adjustments for incoming feed and key furnace parameters (COT, S/HC, COP)
- ANN modeling to predict and adjust run lengths to plan decoking cycle
- LP Model to maximize production options appropriately

Abbreviations: SHC: Steam to Hydrocarbon, COT: Coil Outlet Temperature, COP: Coil Outlet Pressure, ANN: Artificial Neural Network, LP: Linear Programming
Furnace Yield Prediction Models
Predictions provide insights on impact of feed, cracking severity and other production parameters and thereby allow appropriate adjustments to be made to optimize performance and production

### Furnace Coilwise Imbalance - Impact on Conversion, Yields

<table>
<thead>
<tr>
<th></th>
<th>Case-1: Constant severity for differential COT's</th>
<th>Case-2: Differential severity at constant COT's</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coil AB</td>
<td>Coil BA</td>
</tr>
<tr>
<td><strong>HC Feed Rate</strong></td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td><strong>SHC</strong></td>
<td>0.50</td>
<td>0.45</td>
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<tr>
<td><strong>CIP</strong></td>
<td>39.5</td>
<td>42.0</td>
</tr>
<tr>
<td><strong>COP</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Severity Plant Tag</strong></td>
<td>66.6</td>
<td>-</td>
</tr>
<tr>
<td><strong>Severity Calculated</strong></td>
<td>66.6</td>
<td>66.6</td>
</tr>
<tr>
<td><strong>Actual COT(Plant Tag)</strong></td>
<td>1561</td>
<td>1561</td>
</tr>
<tr>
<td><strong>Calculated COT( CoilSim)</strong></td>
<td>1556</td>
<td>1558</td>
</tr>
<tr>
<td><strong>Heat Absorbed</strong></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Effluent (Wt%)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>H2</strong></td>
<td>3.91</td>
<td>3.90</td>
</tr>
<tr>
<td><strong>CH4</strong></td>
<td>6.37</td>
<td>6.50</td>
</tr>
<tr>
<td><strong>C2H4</strong></td>
<td>△51.17</td>
<td>△50.99</td>
</tr>
<tr>
<td><strong>C2H6</strong></td>
<td>32.63</td>
<td>32.60</td>
</tr>
<tr>
<td><strong>C3H6</strong></td>
<td>1.32</td>
<td>1.36</td>
</tr>
<tr>
<td><strong>C3H8</strong></td>
<td>0.24</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Abbreviations: SHC: Steam to Hydrocarbon, CIP: Coil Inlet Pressure, COP: Coil Outlet Pressure, CIT: Coil Inlet Temperature
Utility Of Furnace Yield Models

The furnace yield models provide insights into the furnace operation that helps improve performance

- Furnace Models help identify differential cracking among coils and help identify limiting/fast coking coils
- Propylene, C4, Aromatics optimization based on sensitivity analysis on Severities
- Integrated Radiant Box and Convection section to track furnace efficiencies on daily basis
- Furnace effluent being used as input to plant wide simulation flow sheet for material and energy balance reconciliation
- Yield model outputs used for tracking TLE performance including fouling and steam generation
- Yield model built in Aspen Custom Modeler integrated with planning model in Aspen PIMS
Radiant and Convection Section Models

Ingenero customizes its proprietary heat flux model or commercially available fired heater modeling packages (HTRI) to develop models to match individual furnace geometry

• Combination of radiant and convection section models, aids to monitor and adjust burners to maximize run length and production while ensuring that tube metal temperatures are within allowable limits
  ✓ Determines the parameter settings for maximum safe production
• Further convection section models helps in overall thermal efficiency improvement
  ✓ Prediction/evaluation of convection section individual pass performances
  ✓ Monitoring of fouling in individual passes for both flue gas and process side
  ✓ Identification of possibility of channeling of flue gas
Convection Section Model Utilization Example

Convection section modeling allows maximum throughput without exceeding design tube skin temperature.

**Capacity limitation: DSS design skin temperature**

<table>
<thead>
<tr>
<th></th>
<th>design temp</th>
<th>17:44</th>
<th>14.1</th>
<th>14.5</th>
<th>17:44</th>
<th>14.1</th>
<th>14.5</th>
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<tbody>
<tr>
<td>Hydrocarbon feed</td>
<td>95</td>
<td>15.3</td>
<td>14.1</td>
<td>14.5</td>
<td>15.3</td>
<td>14.1</td>
<td>14.5</td>
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<tr>
<td>Boiler Feed Water</td>
<td>195</td>
<td>14.1</td>
<td>14.5</td>
<td>130</td>
<td>144</td>
<td>130</td>
<td>144</td>
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<tr>
<td>Attemperation water</td>
<td>230</td>
<td>14.1</td>
<td>14.5</td>
<td>226</td>
<td>226</td>
<td>14.1</td>
<td>14.5</td>
</tr>
<tr>
<td>Dilution steam</td>
<td>269</td>
<td>14.1</td>
<td>14.5</td>
<td>249</td>
<td>249</td>
<td>14.1</td>
<td>14.5</td>
</tr>
<tr>
<td>Crossover</td>
<td>418</td>
<td>14.1</td>
<td>14.5</td>
<td>485</td>
<td>485</td>
<td>14.1</td>
<td>14.5</td>
</tr>
<tr>
<td>= Finned Tubes = Bare Tubes</td>
<td>418</td>
<td>14.1</td>
<td>14.5</td>
<td>516</td>
<td>516</td>
<td>14.1</td>
<td>14.5</td>
</tr>
<tr>
<td>HC preheat</td>
<td>509</td>
<td>14.1</td>
<td>14.5</td>
<td>534</td>
<td>534</td>
<td>14.1</td>
<td>14.5</td>
</tr>
<tr>
<td>BFW</td>
<td>572</td>
<td>14.1</td>
<td>14.5</td>
<td>479</td>
<td>479</td>
<td>14.1</td>
<td>14.5</td>
</tr>
<tr>
<td>HC + stm 1</td>
<td>652</td>
<td>14.1</td>
<td>14.5</td>
<td>491</td>
<td>491</td>
<td>14.1</td>
<td>14.5</td>
</tr>
<tr>
<td>HPSS</td>
<td>725</td>
<td>14.1</td>
<td>14.5</td>
<td>698</td>
<td>698</td>
<td>14.1</td>
<td>14.5</td>
</tr>
<tr>
<td>DSS</td>
<td>751</td>
<td>14.1</td>
<td>14.5</td>
<td>727</td>
<td>727</td>
<td>14.1</td>
<td>14.5</td>
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<tr>
<td>HC + stm 2</td>
<td>751</td>
<td>14.1</td>
<td>14.5</td>
<td>751</td>
<td>751</td>
<td>14.1</td>
<td>14.5</td>
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<tr>
<td>Z5 Load, tph</td>
<td>729</td>
<td>14.1</td>
<td>14.5</td>
<td>729</td>
<td>729</td>
<td>14.1</td>
<td>14.5</td>
</tr>
<tr>
<td>Z6 Load, tph</td>
<td>751</td>
<td>14.1</td>
<td>14.5</td>
<td>751</td>
<td>751</td>
<td>14.1</td>
<td>14.5</td>
</tr>
</tbody>
</table>

Z5 Load, tph: 15.3
Z6 Load, tph: 14.1

**Diagram:**
- HC preheat
- BFW
- HC + stm 1
- HPSS
- DSS
- HC + stm 2
- Crossover
- Design temp
- Z5 Load, tph
- Z6 Load, tph
- Design Time (hrs)
- Date (dd/mm)
Technique Utilization Example - CFD

CFD modeling identifies hot spots and channeling and solves potential design flaws.
Case Study 1: Furnace Operation/Coil Balance
Furnace key parameters optimized based on coil-wise results from yield model and radiant section flux model to balance the overall furnace operation resulting in substantial improvement

- Imbalanced furnace operation
  - Results in differential coking in coils (CIP & TLE ΔP deviations)
  - If not controlled, leads to early termination of furnace run length
  - Affects furnace yields, operational efficiency and coil life

<table>
<thead>
<tr>
<th>Imbalanced Furnace Operation</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CIP</td>
<td>Feed</td>
<td>Severity</td>
<td>Yield</td>
</tr>
<tr>
<td>----</td>
<td>------</td>
<td>----------</td>
<td>-------</td>
</tr>
<tr>
<td>Coil AB</td>
<td>33.3</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>Coil BA</td>
<td>34.5</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>Coil BC</td>
<td>31.8</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>Coil CB</td>
<td>40.3</td>
<td>6.6</td>
<td>Max: 67.8%</td>
</tr>
<tr>
<td>Coil CD</td>
<td>34.9</td>
<td>6.5</td>
<td>Min: 65.3%</td>
</tr>
<tr>
<td>Coil DC</td>
<td>35.1</td>
<td>6.2</td>
<td>Avg: 67.1%</td>
</tr>
</tbody>
</table>

Abbreviations: COT: Coil Outlet Temperature, CIP: Coil Inlet Pressure

- Comprehensive coilsim results and flux model was used to initiate actions to balance furnace operation
  - Selection of analyzer location
  - Setting uniform heat flux profile through burner adjustments
  - Adjustment in fuel gas bias, COT bias, instrumentation corrections etc.
Case Study 1: Furnace Operation/Coil Balance

Corrective actions helped in improving overall furnace balance, resulting in sizeable performance improvement

- Feed deviation reduced from 6% to 1%
- Difference in min-max conversions reduced from 2.5 to 0.5
- CIP rise observed to be uniform and rate of rise controlled well

Benefits:
- Balanced operation resulted in uniform coking in coils, which helped in improving furnace performance
- Scope for extending furnace run length and/or severity
- Reduced coking in coils and fouling in TLE’s
  - Lower CIP’s and COP’s
  - Lower coil TMT’s
  - Shorter de coke period
- Improvement in ethylene yield by 1.3 wt%
Statistical Models – PCA For Outlier detection

Statistical models based on PCA (Principal Component Analysis) are developed for furnaces, used for identifying the deviations in normal operation/performance and aid improvement

- Key features and benefits of PCA models
  - Multivariate correlations between several variables captured easily
  - Compares current furnace run with the past performance
  - Possibility of missing out on outliers/abnormal operation is very rare
  - Which variable caused the sample to be an outlier?
    - Q contribution plot gives that insight
  - Model is linked to Process Historian and updates automatically
  - Filtering out outliers is easy and less time consuming
  - Aids in early detection of faults, improves reliability
Outlier detection example using PCA: Contribution Plots

"3" statistical threshold value decided based on value of Q critical. Any Variable crossing this value for a particular sample is treated as an outlier, needs to be investigated further.

Outlier Example:
COP is suspected as an outlier, as value of 21.3 is higher than normal.
Case Study 2: Furnace PCA

Abnormal deviation in furnace operating parameters was accurately detected and subsequent actions helped in reducing differential coking and thereby extending furnace run length.

Model predictions ~ 10th day: Normal Performance

Model predictions ~ 15th day: Some Variation in Performance

Some disturbance was observed in indicated coil feed flow
Case Study 2: Furnace PCA

Model predictions ~ 25th day: Differential coking observed

- PCA model predictions on ~25th day of furnace operation indicated:
  - Higher rate TLE fouling, which may affect furnace runlength
  - Deviation in coil feed flow possibly affecting coil performance/coking

- Based on further analysis, it was identified that drift in indicated coil outlet temperature (COT) which controls the coil feed flow was causing higher coking

- Instrumentation error in COT indication was corrected, additional actions like heat flux balancing was carried out

- Facilitated in extending the furnace runlength considerably
  - Differential coking could have restricted run length to 35 – 40 days
  - Early identification and corrective actions helped in extending furnace run length to 55 days
Furnace Predictions using Partial Least Squares (PLS)

Statistical models based PLS technique is used to predict key furnace parameters to assist identifying deviations precisely and aid furnace performance improvement

• Key features
  ✓ Partial Least Squares (PLS) is a powerful multivariate predictive technique
  ✓ PLS fits equations between dependent and independent variables
  ✓ Coefficient indicates which variable impacts predicted variable the most

• Furnace predictions
  ✓ Model predicts critical furnace parameters such as COT, Feed flow, CIT, COP, CIP etc. based on historical furnace data

• Benefits of PLS models
  ✓ Finding the deviations from normal/best operation accurately
  ✓ Early detection of faults, equipment reliability
  ✓ Assist in root cause analysis and optimizing furnace parameters for given condition

Abbreviations: COT: Coil Outlet Temperature, CIT: Coil Inlet Temperature, COP: Coil Outlet Pressure, CIP: Coil Inlet Pressure
Predictive Analysis: Forecasting Tools
Furnace CPR predictions/forecasting supports furnace scheduling and corrective measures to improve/optimize runlength
LP Models: Optimizer

Based on an objective function (profit/production); customized LP models provide optimal operating parameters settings and distribution of feeds among multiple furnaces.
The Importance Of Furnace Dashboards

Analytics coupled with bird’s eye view dashboards, provide a daily view with context for identification of problems and enabling of action, reducing the cycle time from problem identification to solution and action.
Furnace Reliability Matrix – An Intelligent Dashboard

The furnace reliability matrix is a reliable tool which provides a visual, faster identification of furnace anomalies and deviations based on variations from model prediction.

- Matrix flags of deviation in key furnace parameters from normal.
- Statistical tool based models/equations based on historical data and cross verified by fundamental models being used to predict key furnace operating parameters like COT, CIP, XOT, etc.
- Matrix parameter limits for deviations are variable, as per furnace cracking feed slate and run length.
- Highlights parameters with level of significance and criticality.
- Matrix information would be key to identify and drill down cause of deviation helping to take quicker measures to improve furnace reliability and performance.
Furnace Reliability Matrix Example – An Excerpt
Sample reliability dashboard generated from analysis using the Technology tools, enabling identification and focus for actions

<table>
<thead>
<tr>
<th>Furnace #5</th>
<th>15/Ethane Conversion (%)</th>
<th>XOT</th>
<th>TMT</th>
<th>XOP</th>
<th>TLE DP</th>
<th>TLE Outlet Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Today's</td>
<td>3.58/6.6</td>
<td>1308.5/Coil1</td>
<td>1984.9/Coil4</td>
<td>46.7/Coil3</td>
<td>7/TLEB</td>
<td>730.5/TLEB</td>
</tr>
<tr>
<td>Deviation Yesterday</td>
<td>0.5</td>
<td>-0.9/Coil2</td>
<td>20.2/Coil3</td>
<td>0.9/Coil3</td>
<td>0.4/TLEB</td>
<td>0.8/TLEB</td>
</tr>
<tr>
<td>Deviation 10 Days</td>
<td>-2.49</td>
<td>-2.1/Coil5</td>
<td>63.6/Coil4</td>
<td>6/Coil3</td>
<td>2.5/TLEB</td>
<td>2.3/TLEA</td>
</tr>
<tr>
<td>Deviation SOR</td>
<td>10.2</td>
<td>-9.8/Coil1</td>
<td>142.6/Coil4</td>
<td>15/Coil3</td>
<td>4.5/TLEB</td>
<td>20.6/TLEB</td>
</tr>
</tbody>
</table>

Abbreviations: COT: Coil Outlet Temperature, CIT/XOT: Coil Inlet Temperature, CIP/XOP: Coil Inlet Pressure, TMT: Tube Metal Temperature

### Matrix Deviations
Computed based on:
1. Difference between predicted and actual values
2. Difference between actual value and pre-defined limits based on furnace run length

### Matrix Predicted Values
Predicted value is calculated for key furnace parameters viz. COT, XOT, CIP, TMT based on models calibrated by historical plant measurements and maintained to reflect current conditions.

### Matrix Variable Limits
While furnace operating parameter limits are defined and set to be automatically cross-checked with, as part of the matrix computations and flagging/alert, some parameter limits within the matrix have been set variable to the furnace run length. This is because the significance of certain critical operating parameters like CIP, TMT, TLE ΔP etc. changes with days of operation.
Consistent Improvement In Furnace Run Lengths

Application of multi-model techniques in several ethylene units has been helpful to consistently improve furnace run lengths across various technologies.

<table>
<thead>
<tr>
<th>#</th>
<th>Technology Supplier</th>
<th>Feed Type</th>
<th>Furnace runlength before IPOG (In days)</th>
<th>Furnace runlength with IPOG (In days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Technip</td>
<td>Ethane</td>
<td>50</td>
<td>&gt; 90</td>
</tr>
<tr>
<td>2</td>
<td>Technip</td>
<td>Ethane</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>SWEC</td>
<td>Naphtha</td>
<td>35</td>
<td>55</td>
</tr>
<tr>
<td>4</td>
<td>SWEC</td>
<td>C5 and C6</td>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>KBR</td>
<td>NGL</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>SELLAS</td>
<td>Ethane</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>7</td>
<td>LUMMUS</td>
<td>Ethane/Propane</td>
<td>55</td>
<td>Sustained with 55 - 60 days with 8% Feed Increase</td>
</tr>
</tbody>
</table>
Case Example of Benefits: Ethylene Facility

Data analytics combined with Industrial Internet of Things (I-IoT) enabled Remote and focused working, generate significant bottom line results if implemented and operated properly.

- Increased capacity without capex
  - Cumulative measured value addition of $200 million over 5 years
  - Returns ~70 times the cost to put solution in place and sustain
  - Helped run the plant an extra year before a turnaround, optimally
  - Early detection of furnace tube leak to avert tube failure
  - Failure predictions and residual life analysis prevented multiple safety/maintenance events
  - Debottlenecking study at 50% cost and time for 25% capacity increase
  - Multiple cases of early detection of anomalous conditions prevents a plant upset

- Increased raw material conversion efficiency
The Necessary Three For True Value Capture

Technology tools, knowledge of both analytical techniques and manufacturing process, and appropriate methodology to ensure implementation are required for value capture and sustenance.

**Results**

- **Knowledge value**: To interpret the analysis provide by the tools and link it to actions.
- **Methodology value**: To ensure the results are understood and utilized, actions taken and tracked.
- **DMAIC involvement**: Define, Measure, Analyze, Improve and Control.
- **Technology value**: Best-of-breed tools & analytics.
- **Daily Operations Data**: Functional Experts - best practices.
Excellence Through Insight

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