FOULING IN A STEAM CRACKER CONVECTION SECTION PART 1:
A HYBRID CFD-1D MODEL TO OBTAIN ACCURATE TUBE WALL TEMPERATURE PROFILES

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CRUDE OIL AND HYDROCARBON FLUID FOULING

8. Thermal Fouling of Heat Exchanger Tubes due to Heavy Hydrocarbon Droplets Impingement
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REBOUND | STICK | BREAKUP

SPLASH
Introduction: steam cracker

ExxonMobil says Singapore ethylene unit will crack crude

11:24 AM MST | January 10, 2014 | —Deepti ramesh

ExxonMobil Chemical says its recently started ethylene plant in Singapore can crack crude oil as feedstock, eliminating the refining steps needed to produce naphtha. ExxonMobil officially opened its expanded Singapore chemical complex on 8 January.

ExxonMobil Chemical president Stephen Pryor told attendees at the opening that the "unit can process an unprecedented range of feedstocks—from light gases to heavy liquids." ExxonMobil says the Singapore unit is the first steam cracker that can use crude as a feedstock.

Introduction: convection section

Liquid Feed → Evaporator → Flue gas out

Feed → Superheated Steam

Nozzle

Feed-steam mixture overheater-1

Evaporator

Steam super heater

Mixture over heater-1

Mixture over heater-2

Mixing nozzle

Flue gas in

~ 1400 K

~ 700 K
Introduction: convection section

Heavy Liquid Feed

Feed

Nozzle

Superheated Steam

Evaporator

Flue gas in ~ 1400 K

Flue gas out ~ 700 K

Mixture over heater-1

Mixture over heater-2

Steam super heater

Evaporator

Mixing nozzle

Feed-steam mixture overheater-1

Impinging droplets → Coke formation
Tube fouling mechanism: liquid film

Droplet impinging on the tube wall

Formation of liquid film

Amount of liquid deposition

Weber number \((\Phi_{\text{droplet}}, v_{\text{droplet}}, \text{etc.})\)

Wall temperature
Tube fouling mechanism: coke formation

Liquid subjected to high temperature

- Formation of **asphaltenes**

- Asphaltenes > solubility limit

- Formation of **coke particle**

- Sedimentation & stick to the wall

High flue gas temperature
Coke layer:
- Hampers heat transfer
- Shutdown

Study of fouling layer:
- Designing new convection section designs mitigating fouling
Formation coke layer highly dependent on **Wall temperature**

**This study**

Obtain accurate wall temperature profiles

Coupling Flue gas side – Process gas side

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Case study: geometry

Convection section

High sensibility to fouling

Mixture overheater 1 & 2 are simulated
**Convection section**

**Simulation domain**

- Mixture overheater 1
- Mixture overheater 2

**Flue gas**
Case study: Feed & Operating conditions

**Hydrocarbon feed**

- **Evaporator**
- **Steam over heater**
- **Mixture over heater 1**
- **Mixture over heater 2**

**Flue gas**

<table>
<thead>
<tr>
<th>Component</th>
<th>Wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>72.5</td>
</tr>
<tr>
<td>O₂</td>
<td>2.6</td>
</tr>
<tr>
<td>CO₂</td>
<td>13.3</td>
</tr>
<tr>
<td>H₂O</td>
<td>11.6</td>
</tr>
</tbody>
</table>

- Inlet mixture over heater 1
  - Evaporated feed
  - Inlet temperature = 526 K
  - Mass flow rate = 8.8 kg/s
  - Steam dilution = 1 kg/kg

- Inlet temperature = 1450 K
- Mass flux = 1.41 kg/(m²s)
- Inlet pressure = 1 bar
Heat fluxes and wall temperature have to be obtained
Flue gas side

Crossflow of gas over a tube bundle

Formations of circulation zones at top of tube

CFD model has to accurately describe the flow over the tubes
Flow structure of crossflow

INLINE

Two symmetrical vortices

STAGGERED

One wake

Flue gas

Y velocity

m/s

32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
Flue gas side: CFD model

ANSYS FLUENT 15.0

Turbulence model

- Important for heat transfer around tube
- Reynolds stress model captures symmetrical vortices

Geometry

- 2D geometry to save computational cost
- 1.2 millions cells
**Process gas side: 1D model**

**Process gas side** → Single phase forced convection

### FLUID TEMPERATURE

**Steady state energy balance**

\[ \dot{m} d(c_p T_b) = q_{wall} P dz \]

Area weighted average heat flux from CFD simulation

### WALL TEMPERATURE

**Boundary condition for CFD simulation**

\[ T_{wall} = \frac{U}{q_{wall}} + T_b \]

\[ \frac{1}{U} = \frac{1}{h} + \frac{d_i}{2\kappa} \ln \frac{d_o}{d_i} \]

\[ Nu = 0.023Re^{4/5}Pr^n \]
Process gas side: compartmentalization

Separation point

Re-attachement point

Divide tube in three zones
Calculation $T_{wall,i}$ per zone:

$$T_{wall,i} = \frac{U}{q_{wall,i}} + T_b$$

BC for CFD simulation
Size compartments determined based on **shear stress** profile

Y velocity $m/s$

![Diagram showing shear stress profile and compartment angles for tube 4](image)

**Compartment angles of tube 4**

- Separation point
- Re-attachment point
- Staggered
### Tube outlet temperature

<table>
<thead>
<tr>
<th>Tube nr.</th>
<th>Outlet Temperature K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1D</td>
</tr>
<tr>
<td>1</td>
<td>874</td>
</tr>
<tr>
<td>2</td>
<td>892</td>
</tr>
<tr>
<td>3</td>
<td>888</td>
</tr>
<tr>
<td>4</td>
<td>889</td>
</tr>
<tr>
<td>5</td>
<td>885</td>
</tr>
<tr>
<td>6</td>
<td>887</td>
</tr>
<tr>
<td>7</td>
<td>895</td>
</tr>
<tr>
<td>8</td>
<td>876</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>886</strong></td>
</tr>
</tbody>
</table>

- **Equal outlet temperatures**
- **Close to typical reactor inlet ~890K**
- **Outer tubes have less heat input**
- **Lower velocities at the side of the convection section**
Results: heat fluxes

Average wall heat flux

- Higher upper compartment
- Higher velocity at the sides
- Higher heat transfer
Results: profiles

Heat flux profiles

Wall temperature profiles

\[ T_{wall}(\gamma) = \frac{q_{wall}(\gamma)}{U} + T_b \]
Comparison

No difference $\rightarrow$ **Average properties** (tube outlet temperature, average heat flux)

Difference $\rightarrow$ **Maximum heat flux** Coke layer profile

![Graphs showing heat flux and temperature differences](image)
Comparison

No difference → **Average properties** (tube outlet temperature, average heat flux)

Difference → **Maximum heat flux** → Coke layer *profile*

Number of compartments

Difference in maximum heat flux
Procedure to couple the flue gas side and the tube side of a convection section is developed

Flue gas side and process gas side models are developed

The effect of compartmentalization of the tube passes in the process gas side model is considerable. The ideal number of compartments has to be studied.

Accurate tube wall temperatures are obtained. The next step is to use these profiles in a fouling study