Feasibility Study of a Turbo-Cracker

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Outline

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Ethylene is the largest volume building block for many petrochemicals.

Currently, thermal cracking technology provided by ABB Lummus Global, Shaw Stone and Webster, Kellogg Brown & Root, Linde, and KTI.

Thermal Cracking Furnace: tubular reactors where thermal cracking of hydrocarbon takes place.

Cracking reactions are endothermic. Lots of energy transferred through the tube wall.
Thermal Cracking Furnace: Current Status

- Coke is formed during pyrolysis. Steam is added as a diluent to the feed.
- Product at the tubular reactor outlet must be cooled down quickly to avoid any further cracking.
- Currently transferline exchanger is used.
Thermal Cracking Furnace: Current Status

- Disadvantage/drawback in existing Thermal Cracking Furnace
  - Since thermal cracking reaction is very sensitive to temperature, high heat flux through tube walls is required, high surface temperature is involved.
  - At this high surface temperature, heavy coke deposits is formed during normal operation. De-coking every 40 to 100 days. Coking limits heat transfer, also reduces ethylene selectivity.
  - Thermal Cracking Furnace is huge in volume (approximately 10,000 m$^3$).
The Idea of Turbo-Cracker

- Use Compressor and Turbine to replace the existing thermal cracking furnace, so-called Turbo-Cracker.
- Heat is provided by compression in the Compressor of a Gas Turbine (GT).
- Product at the tubular reactor outlet is expanded with the Turbine of a Gas Turbine (GT).
The Idea of Turbo-Cracker

● Advantages
  ● Higher temperature of the mixture of hydrocarbon and steam will increase the selectivity of ethylene.
  ● Residence time should be much shorter.
  ● Product at the tubular reactor outlet expands rapidly in the Turbine. This also helps to improve ethylene selectivity.
  ● Coking will be less severe since no heat is transferred across the tube wall.
  ● One GT (Compressor and Turbine only) can replace several existing thermal cracking furnaces due to its high processing capacity.
Modelling of Propane Pyrolysis

● Reaction Scheme in Froment (1975)

(1) \( \text{C}_3\text{H}_8 \rightarrow \text{C}_2\text{H}_4 + \text{CH}_4 \)  \( A=1.6\times10^9 \)  \( E=44 \text{ kcal/mole} \)
(2) \( \text{C}_3\text{H}_8 \rightarrow \text{C}_3\text{H}_6 + \text{H}_2 \)  \( A=2.0\times10^9 \)  \( E=44 \text{ kcal/mole} \)
(3) \( 2\text{C}_3\text{H}_8 \rightarrow \text{C}_2\text{H}_6 + \text{C}_4\text{H}_{10} \)  \( A=2.2\times10^9 \)  \( E=54 \text{ kcal/mole} \)
(4) \( 2\text{C}_3\text{H}_8 \rightarrow \text{C}_3\text{H}_6 + \text{C}_2\text{H}_6 + \text{CH}_4 \)  \( A=1.1\times10^9 \)  \( E=48 \text{ kcal/mole} \)
(5) \( \text{C}_2\text{H}_6 \rightarrow \text{C}_2\text{H}_4 + \text{H}_2 \)  \( A=0.34\times10^{13} \)  \( E=60 \text{ kcal/mole} \)
(6) \( 2\text{C}_2\text{H}_6 \rightarrow \text{C}_2\text{H}_4 + 2\text{CH}_4 \)  \( A=3.9\times10^9 \)  \( E=67 \text{ kcal/mole} \)
(7) \( 2\text{C}_2\text{H}_6 \rightarrow \text{C}_3\text{H}_8 + \text{CH}_4 \)  \( A=0.5\times10^9 \)  \( E=50 \text{ kcal/mole} \)
(8) \( 2\text{C}_3\text{H}_6 \rightarrow 3\text{C}_2\text{H}_4 \)  \( A=1.3\times10^9 \)  \( E=50 \text{ kcal/mole} \)
(9) \( \text{C}_3\text{H}_6 + \text{H}_2 \rightarrow \text{C}_2\text{H}_4 + \text{CH}_4 \)  \( A=1.0\times10^{15} \)  \( E=60 \text{ kcal/mole} \)
(10) \( \text{C}_3\text{H}_6 \rightarrow \text{C}_2\text{H}_2 + \text{CH}_4 \)  \( A=1.4\times10^9 \)  \( E=50 \text{ kcal/mole} \)
(11) \( \text{C}_2\text{H}_4 + \text{H}_2 \rightarrow \text{C}_2\text{H}_6 \)  \( A=0.68\times10^{13} \)  \( E=52 \text{ kcal/mole} \)

Modelling of Propane Pyrolysis

- Reaction Scheme in Froment (1975)

12. \( \text{C}_2\text{H}_4 \rightarrow \text{C}_2\text{H}_2 + \text{H}_2 \quad A=6.0\times10^{13} \quad E=76\text{kcal/mole} \)

13. \( 3\text{C}_2\text{H}_4 \rightarrow 2\text{C}_3\text{H}_6 \quad A=1.3\times10^{11} \quad E=45\text{kcal/mole} \)

14. \( 2\text{C}_2\text{H}_2 + \text{H}_2 \rightarrow \text{C}_4\text{H}_6 \quad A=6.0\times10^{13} \quad E=45\text{kcal/mole} \)

15. \( \text{C}_2\text{H}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{CO} + 3\text{H}_2 \quad A=3.5\times10^{11} \quad E=62\text{kcal/mole} \)

16. \( \text{C}_2\text{H}_2 + \text{C}_3\text{H}_6 \rightarrow \text{C}_5\text{H}_8 \quad A=9.0\times10^{16} \quad E=64\text{kcal/mole} \)

Of these 16 reactions,

(5) and (11) are forward and reverse reactions;

(8) and (13) are forward and reverse reactions;

Modelling of Propane Pyrolysis

- Simulation based on pilot plant in Froment 1975
Modelling of Propane Pyrolysis

Simulation based on pilot plant in Froment (1975)

Feed conditions

- Steam dilution rate: 0.4 kg steam / kg C3H8 (i.e. steam mass fraction 0.2857)
- Pressure: 3 bar
- Temperature: 600 °C
- Mass Flowrate: 0.7655 kg/s

Product conditions

- Pressure: 2 bar
- Temperature: 838 °C
- Mass Flowrate: 0.7655 kg/s

Plug Flow Reactor details

- Length: 95m
- Diameter: 0.108m
- Wall thickness: 0.008m
Conclusions from simulating the pilot plant in Froment (1975):

- At the same operating conditions (P, T and flowrate) for the PFR as described in Froment (1975)
- The product composition is close to those data published in Froment (1975)
- This shows the HYSYS model can be used as the basis of various case studies.
Case Studies

- To investigate the relationship between tubular reactor outlet temperature and the residence time
  - The criterion is to achieve the same propane conversion.
- To investigate the pressure impact

- The reaction kinetics in Froment (1975) were used. These were obtained from 650 °C to 900 °C and under pressure about 3 bars.
- Actually wider pressure range and temperature range are used in the Cases studied.
Case Studies

- **Base Case Design**
  - Use the Reaction Scheme in Froment (1975)
  - Feed same as before
  - PFR details (D=0.108m, L=95m and one long tube only)
  - Operating conditions slightly changed
    - Pressure decreases linearly from 3 bar to 2 bar
    - Temperature increases linearly from 600 °C to 880 °C (Since only outlet temperature at 880 °C, can the propane conversion and ethylene selectivity be similar as before).
  - Residence time: about 970 ms (calculated with average density)
Case Studies

● Summary of results from cases studied
  ● Same mass flowrate for mixture of propane and steam
  ● Temperature still around 3 bar
  ● Reactor length varied from 95 m to 25 m, 6m and 2.5 m
  ● Residence time decrease about 0.9s to 0.28s, 0.06s and 0.027s
  ● Outlet temperature increased 880°C to 965 C, 1084 C and 1170 C to achieve the same propane conversion.

● For 2.5m length reactor, when pressure increased from 3 bar to 6 bar, 9 bar, outlet temperature required from 1170 C decrease to 1099 C, 1061 C and the product yield for ethylene and propylene increased.
  ● This means increasing pressure helps to speed up reaction.
Simulation of Turbo-Cracker

- A standard Compressor is chosen with
  - Compressor Pressure Ratio 23.3:1
  - 17 stages
  - Mass Flow rate 84.5 kg/s (for air)
  - Diameter approximately 2 m and 2.5 m in length

- A standard Turbine is chosen with
  - 6 stage power turbine
  - Diameter approximately 1.5 m and 1.0 m in length

- The same feed is used as in Froment (1975)
- The results from the simulation indicates that
  - Slightly more steam is required to achieve the same propane conversion.
  - One Compressor and Turbine can process 4-5 times of the flowrate of existing thermal cracking furnaces.
Conclusions

- Preliminary simulation indicates that Turbo-Cracker concept worth exploring in more detail.
- The main advantage is that one Turbo-Cracker can replace 4-5 conventional Thermal Cracking Furnaces and is much smaller.

Main Challenges
- The kinetics of thermal cracking of propane and naphtha under higher pressure are not clear.
- Information on existing commercial thermal cracking furnace not enough.
- Compressor requires more power than Turbine can generate.
Thanks for your attention!