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Dynamic Effects of Diabatization in Distillation Columns

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Presentation Outline

Motivation

- Increasing focus on environmental issues and resource management
- Distillation is a widely used separation process in the industry, but it is highly energy intensive. Some key numbers for USA in 1988:
    - Distillation accounted for 4% of the total energy consumption [1]
    - Roughly 40% of the processing energy used in refining and continuous chemical processes was used for distillation
- Conventional distillation columns operate at low efficiencies [2]
- Diabatic distillation columns **can** provide:
    - Higher efficiencies [3]
    - Less utilities and thus less operation cost [4]

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[1] Humphrey, J.L. et al., Separation process technology, McGraw-Hill, 1997

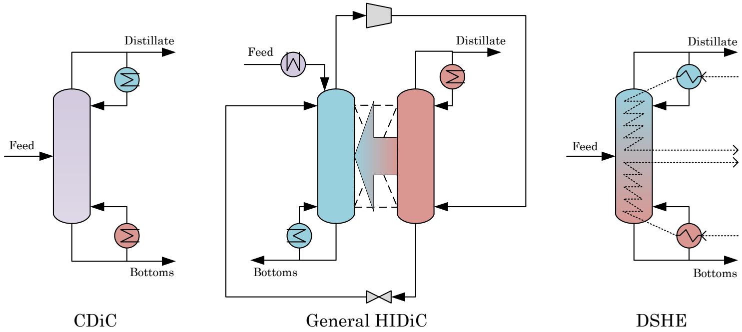
[2] de Koeijer, G. et al., 2000, Int. J. Applied Thermodynamics 3(3):105–110

[3] Nakaiwa, M. et al., 1998, Appl. Therm. Eng., 18(11), 1077–1087

[4] Olujic, Z. et al., 2003, J. Chem. Technol. Biotechnol. 78(2-3):241–248

Introduction (1/3)

- **Adiabatic operation:** Heat is added at the highest temperature (reboiler) and heat is removed at the lowest temperature (condenser), thereby preventing integration (e.g. conventional,...)
- **Diabatic operation:** Heat required to perform the separation is added and/or removed throughout the column (e.g. HIDiC, DSHE, ...)



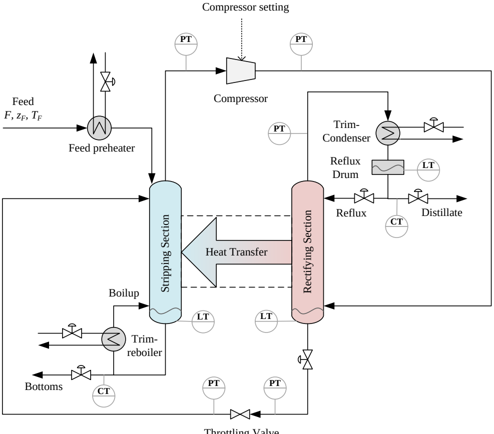
Introduction (2/3)

- **Research example:** Verification of high heat transfer performance and enhanced mass transfer performance in a pilot scale (0,8 m diameter) test unit at TU Delft [5]

[5] http://www.ecn.nl

Introduction (3/3)

The Heat-Integrated Distillation Column (HIDiC)



CT: Composition Transmitter

LT: Level Transmitter

PT: Pressure Transmitter

Methodology

- Formulate generic, dynamic first-principle model describing:
    - Adiabatic distillation columns (Conventional)
    - Diabatic distillation columns (HIDiC)
- Implement model in simulator (Matlab®)
- Formulate realistic case-studies and perform numerical simulations
- Dynamic controllability analysis and compare distillation control configurations on decentralized 2×2 system (remaining perfectly controlled)
- Perform closed-loop simulations based on single-loop control strategies

Dynamic Modeling

- Model features:
  - Binary separation of benzene-toluene with **equally sized** rectifying and stripping section
  - **Mass balances**
  - **Energy balances**
  - Liquid tray hydraulics (variable liquid tray holdups)
  - One mathematical term distinguishes configuration (adiabatic, diabatic)
- Major assumptions:
  - Equilibrium stage model
  - Lewis/Randall ideal mixture
  - **Constant pressure** in each section
  - Negligible vapor holdup compared to liquid holdup
  - Negligible changes in sensible heat
  - Homogeneous stages (ideally mixed)

Simulation Study

- Considered distillation column configurations:
  - Conventional distillation column (CDiC)
  - Heat-Integrated Distillation Column (HIDiC)

Selected model parameters:

Parameter	Value
Top purity	99% benzene
Bottom purity	95% toluene
Number of stages	20
Feed stage location	11
Feed flow	100 $\frac{\mathrm{kmol}}{\mathrm{h}}$
Feed benzene content	0.50
Stripping section pressure	0.1013 MPa
Hydraulic time constant	0.0042 h
Heat of vaporization	30,001.1 $\frac{\mathrm{kJ}}{\mathrm{kmol}}$
Relative volatility	**2.317**
Heat transfer rate	**9,803** $\frac{\mathrm{kJ}}{\mathrm{h \cdot K}}$

Results - Open-loop (1/2)

Dynamic responses to step-changes in disturbance variables.

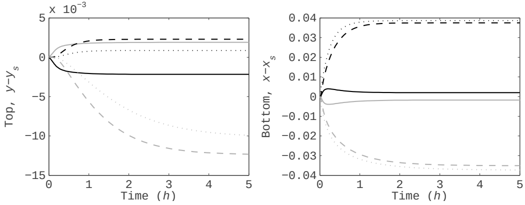
Black curves: +5%
Gray curves: -5%

Legends:
Dashed lines: HIDiC

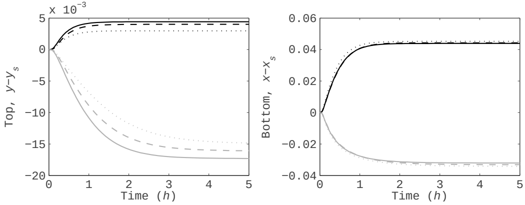
Dotted lines: CDiC

(**Solid lines:** HIDiC without condenser and reboiler)

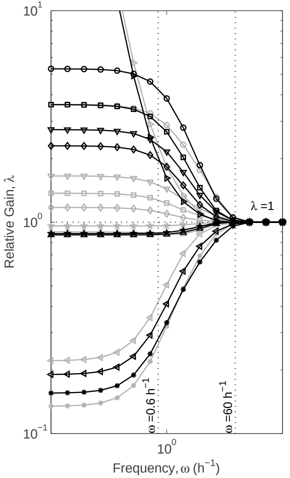
Feed flow rate

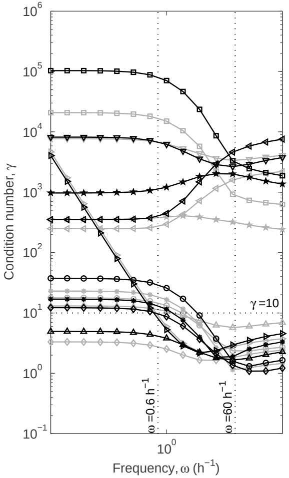


Feed composition



Results - Open-loop (2/2)





Controllability Analysis

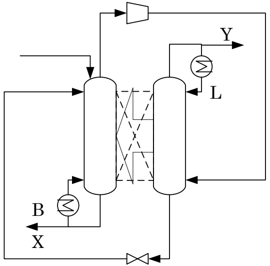
Dynamic RGA Analysis and SVA applied on a decentralized 2×2: **HIDiC (black lines)** and a **CDiC (gray lines)**.

Legends:

(○): LV
(∗): DV
(□): $(L/D)V$
(△): LB ⟵
(▽): $L(V/B)$
(▷): DB
(◁): $D(V/B)$
(⋆): $(L/D)B$
(◊): $(L/D)(V/B)$

Results - Closed-loop (1/2)

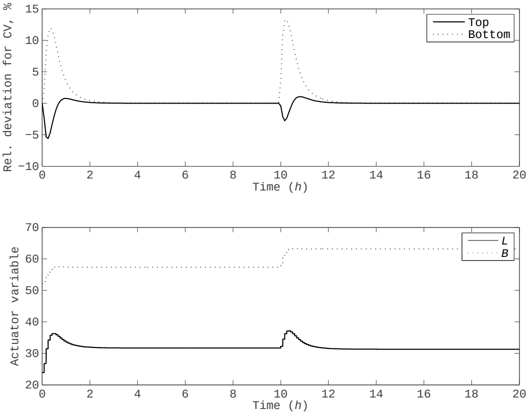
- SISO controller based on an approximated First-order-Plus-Time-Delay model



- Transfer function:

$$\begin{bmatrix} dY \\ dX \end{bmatrix} = \begin{bmatrix} \frac{-0.04972}{0.1336s+1} & \frac{-0.2566}{0.5070s+1}e^{-0.0545s} \\ \frac{-0.009427}{0.055465s+1}e^{-0.0897s} & \frac{0.3144}{0.4357s+1} \end{bmatrix} \begin{bmatrix} dL \\ dB \end{bmatrix}$$

Results - Closed-loop (2/2)



Closed-loop responses for the HIDiC to:

$t = 0\text{h}$: +10% step-change in feed flow rate

$t = 15\text{h}$: -10% step-change in feed composition

Tuning parameters (From S-IMC):

$dL \rightarrow dY_D$:
$K_c = -0.0790,\ \tau_I = 0.5158\text{h}$

$dB \rightarrow X_B$:
$K_c = 8.3147,\ \tau_I = 0.4357\text{h}$

Conclusion

- A flexible and generic model have been developed to describe various diabatic distillation column configurations
- Various feasible pairings exist for the HIDiC
- Diabatization causes increased coupling between input-output variables
- In this study, among others an LB-structure seemed to be a promising control structure for a HIDiC

Future Work

- PhD Project initiated with the title **Operation and Design of Diabatic Distillation Processes**
- Develop detailed model framework for adiabatic and diabatic distillation processes
- Investigations, including:
    - Thermodynamics: Impact on complex thermodynamic modeling on e.g. dynamics
    - Operability: Abnormal operation, e.g. steady-state multiplicity
    - Control: Development of regulatory and multivariable control strategies

End

Thank you for your attention