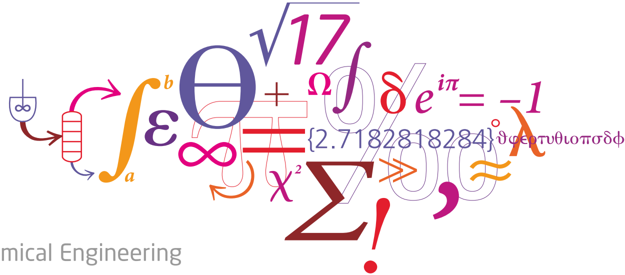
Optimal Operation and Stabilising Control of the Concentric Heat-Integrated Distillation Column (HIDiC)

Thomas Bisgaard[1], Jakob K. Huusom[1], Sigurd Skogestad[2], Jens Abildskov[1]

[1]CAPEC-PROCESS Research Centre, DTU

[2]Process Systems Engineering, NTNU



DTU Chemical Engineering
Department of Chemical and Biochemical Engineering

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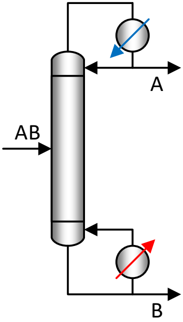
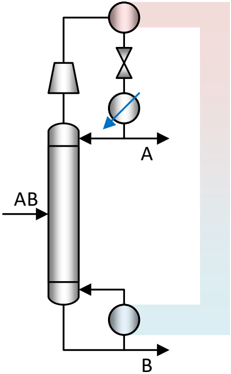
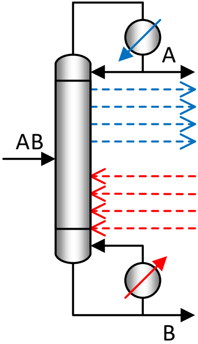
Distillation Concepts



Conventional Distillation

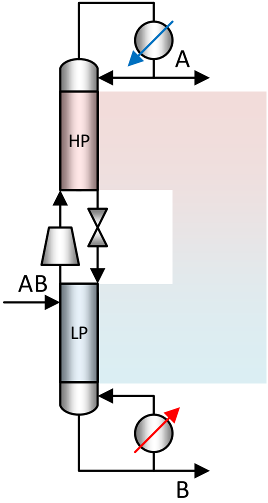


Heat-pump Assisted Distillation

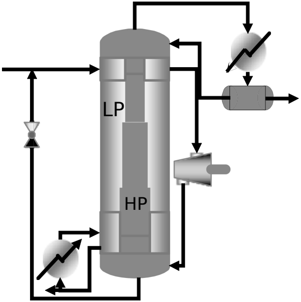


Diabatic Distillation

The Heat-Integrated Distillation Column (HIDiC)



Conceptual illustration of HIDiC.



Example of HIDiC realisation:
The concentric HIDiC

Motivation

- Distillation has a reputation of being an energy consuming and energy inefficient separation technique
- Yet, it is the most common method of separating liquid mixtures
- It is estimated that 40,000 distillation columns are currently in operation[1]
- Significant energy savings are reported in simulation and experimental studies of heat-integrated distillation configurations

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[1] A.A. Kiss. Distillation technology-still young and full of breakthrough opportunities. *J Chem Technol Biotechnol*, 89(4):479–498, 2013

Methodology

Problem definition:

- Design a regulatory (stabilising) control layer
- Design a supervisory (economic) control layer
- Ultimately: Formulate a design method of the above items using a systematic method[2]

Results:

- DYCOPS 2016 [3]
- Manuscript in preparation [4]

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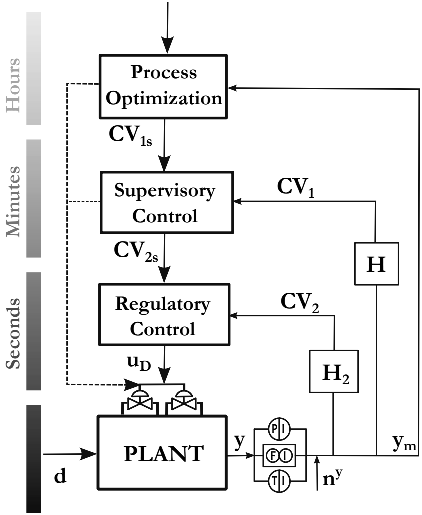
[2] T. Larsson and S. Skogestad. Plantwide control–a review and a new design procedure. *Model Ident Control*, 21(4):209–240, 2000

[3] T. Bisgaard, S. Skogestad, J.K. Huusom, and J. Abildskov. Optimal operation and stabilising control of the concentric heat-integrated distillation column. *11th IFAC International Symposium on Dynamics and Control of Process Systems – Trondheim, Norway*, 2016

[4] T. Bisgaard, S. Skogestad, J.K. Huusom, and J. Abildskov. Optimal operation and stabilising control of the concentric heat-integrated distillation column (hidic). 2016

Control Hierachy



- Process optimisation:
  - Ensure optimal performance
- Supervisory control:
  - Economic control
  - Typically gives set points to regulatory layer
- Regulatory control:
  - Stabilise plant
  - Provides fast control
  - Actuators (valves)
- Plant
  - Responses take place and some are measured

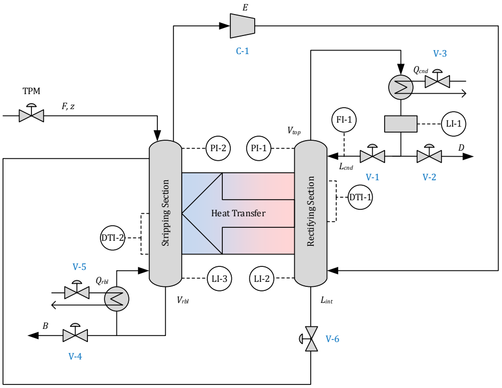
Degrees of Freedom Analysis

Control degrees of freedom:

$$\mathrm{DOF}_{\mathrm{control}} = N_{\mathrm{valves}} = 7 \text{ (Six valves and the compressor)}$$

Number of steady state DOF becomes:

$$\mathrm{DOF}_{\mathrm{ss}} = N_{\mathrm{valves}} - N_{\mathbf{y}0} - N_{\mathbf{u}0} = 7 - 3 - 0 = 4 \qquad (1)$$



Control Structure Design

Top-Down Analysis: Selection of Economic CVs (CV_1)

- Optimal operation:

$$\begin{aligned}\min_{\mathbf{u}_s} J = {} & S_F(\mathbf{z})m_F - S_D(\mathbf{x}_D)m_D - S_B(\mathbf{x}_B)m_B \\ & + S_{steam}m_{steam} + S_{cw}m_{cw} + S_{electricity}E \\ \text{s.t. } & x_{D,imp} \leq x_{D,imp,max} \\ & x_{B,imp} \leq x_{B,imp,max} \\ & P_{min} \leq P_i \leq P_{max} \quad i = 1, 2, \ldots, N_S \\ & L_{min} \leq L_i \leq L_{max} \quad i = 1, 2, \ldots, N_S - 1 \\ & V_{min} \leq V_i \leq V_{max} \quad i = 2, 3, \ldots, N_S \\ & 0 \leq E \leq E_{max} \\ \text{with } & \mathbf{u}_s = [P_{str}, CR, L_{cnd}, Q_{rbl}]\end{aligned} \tag{2}$$

- Active constraints? $P_{str} = P_{min}$? $L_{cnd} = L_{min}$?

Bottom-up Analysis: Stabilising Control Scheme

Identification of CV$_2$'s[5] and pairing with MV's:

CV$_2$		Indicator	u	Valve
Temperature profile	ΔT	DTI-1/DTI-2	Q_{cnd}	V-3
Stripping section pressure	P_{str}	PI-2	Q_{rbl}	V-5
Rectification section pressure	P_{rct}	PI-1	E	V-3
Condenser holdup	M_{cnd}	LI-1	D	V-2
Rectification section holdup	M_{rct}	LI-2	L_{rct}	V-6
Stripping section (reboiler) holdup	M_{rbl}	LI-3	B	V-4
No dry spots (if L_{min})	L_{cnd}	FI-1	L_{cnd}	V-1

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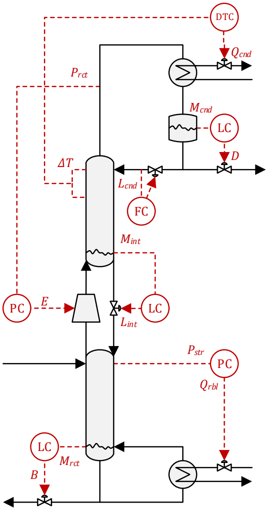
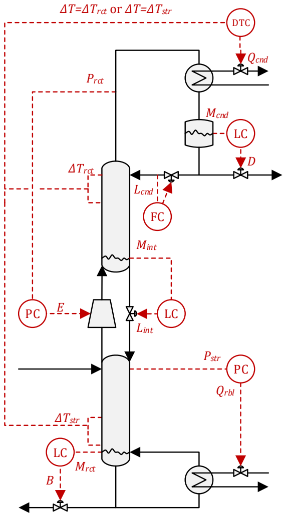
[5] S. Skogestad. The dos and don'ts of distillation column control. *Chem Eng Res Des*, 85(A1):13–23, 2007

Bottom-up Analysis: Stabilising Control Scheme



Distillate more valuable.



Bottoms more valuable.

Economic Control

- Supervisory control layer design
- Purpose: Keep (primary) controlled outputs at optimal setpoints, using
    - setpoints for the regulatory layer
    - any unused manipulated variables
- Decentralised or multivariable control?
- Coordination (e.g. for multiple active constraint regions)?

Dynamic Model

- A more elaborate model documentation and solution procedure is presented in previous work[6]
- The key features of the model are:
    - Equilibrium-stage model (ideal vapour phase)
    - Time-varying tray pressure drops
    - Liquid hydraulics $L = f(H_{oW}, \ldots)$
    - Vapour hydraulics $V = f(\Delta P, \ldots)$

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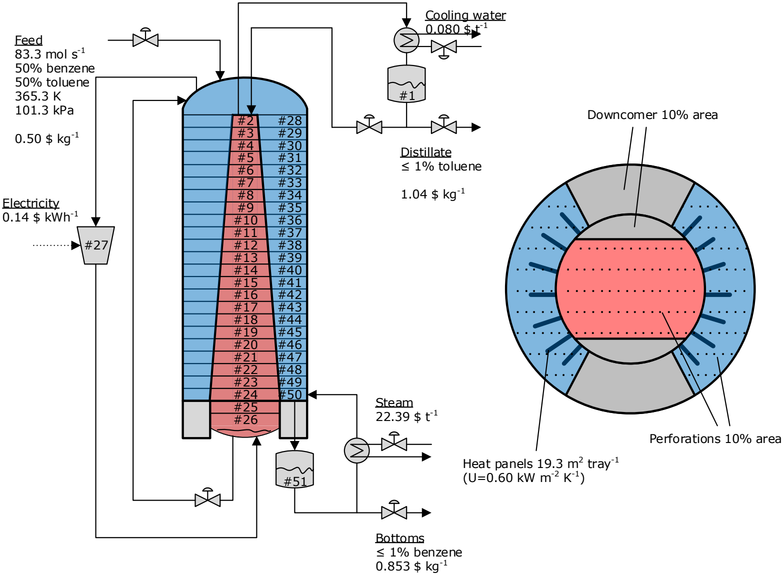
[6] T. Bisgaard, J.K. Huusom, and J. Abildskov. Modeling and analysis of conventional and heat-integrated distillation columns. *AIChE Journal*, 61(12):4251–4263, 2015

Case Study I: Benzene/toluene

Separation and Design Formulation



Feed
83.3 mol s^{-1}
50% benzene
50% toluene
365.3 K
101.3 kPa

0.50 \$ kg^{-1}

Electricity
0.14 \$ kWh^{-1}

Cooling water
0.080 \$ t^{-1}

Distillate
≤ 1% toluene

1.04 \$ kg^{-1}

Steam
22.39 \$ t^{-1}

Bottoms
≤ 1% benzene
0.853 \$ kg^{-1}

Downcomer 10% area

Perforations 10% area

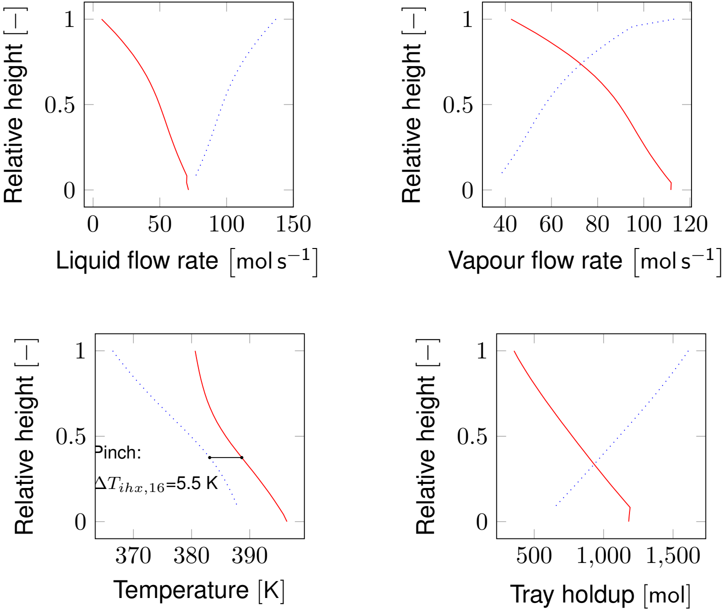
Heat panels 19.3 m^2 $tray^{-1}$
(U=0.60 kW m^{-2} K^{-1})

Nominal Optimal Operating Point

	Variable	Unit	Configuration	
			CDiC	HIDiC
Design degrees of freedom	P_{str}	kPa	101.3	101.3
	CR	-	-	2.306
	L_{cnd}	$\mathrm{mol\,s^{-1}}$	60.15	0.8333
	Q_{rbl}	kW	3304	1175
Cost function	J	$\$\,\mathrm{s^{-1}}$	-3.068	-3.081
Constraints (bold: red)	x_D	-	**0.9900**	**0.9900**
	$1 - x_B$	-	0.9987	**0.9900**
	$\min L_i$	$\mathrm{mol\,s^{-1}}$	55.66	**0.8333**
	$\max L_i$	$\mathrm{mol\,s^{-1}}$	141.8	136.9
	$\min V_i$	$\mathrm{mol\,s^{-1}}$	97.69	35.3
	$\max V_i$	$\mathrm{mol\,s^{-1}}$	102.2	113.1
	$\min P_i$	kPa	**101.3**	**101.3**
	$\max P_i$	kPa	135.8	234.0
	E	kW	-	357.6

Case Study I: Benzene/toluene

Nominal Optimal Operating Point

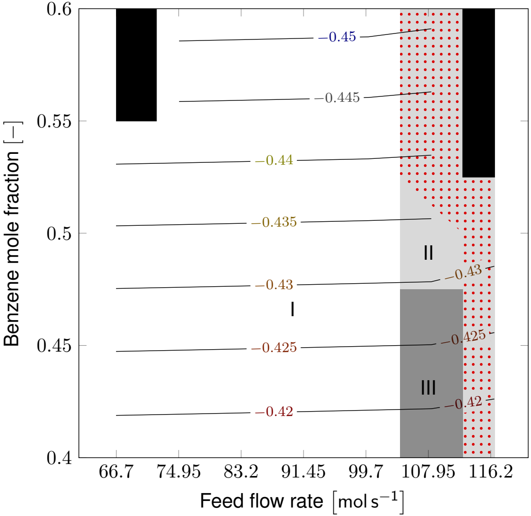


Pinch:

$\Delta T_{ihx,16}$=5.5 K

Case Study I: Benzene/toluene

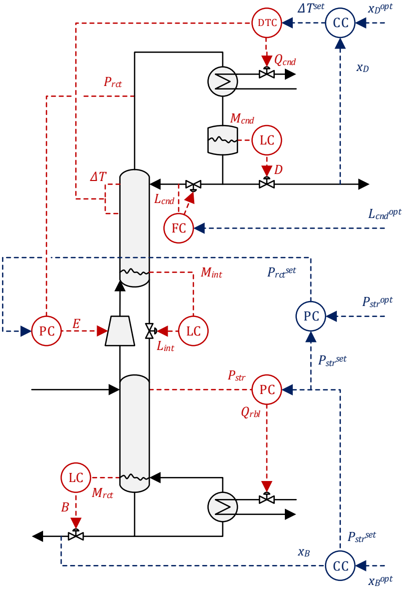
Active constraint Regions – Optimal Operation During Disturbances



Legend:
I: $\{x_D, x_B, P_{min}, L_{min}\}$
II: $\{x_D, x_B, P_{min}, V_{max}\}$
III: $\{x_D, x_B, P_{min}, L_{min}, E_{max}\}$
Black: Infeasible
Red-dotted: Entrainment flooding
Contours: J/m_F [=] \$ kg^{-1}

Case Study I: Benzene/toluene

Control Configuration

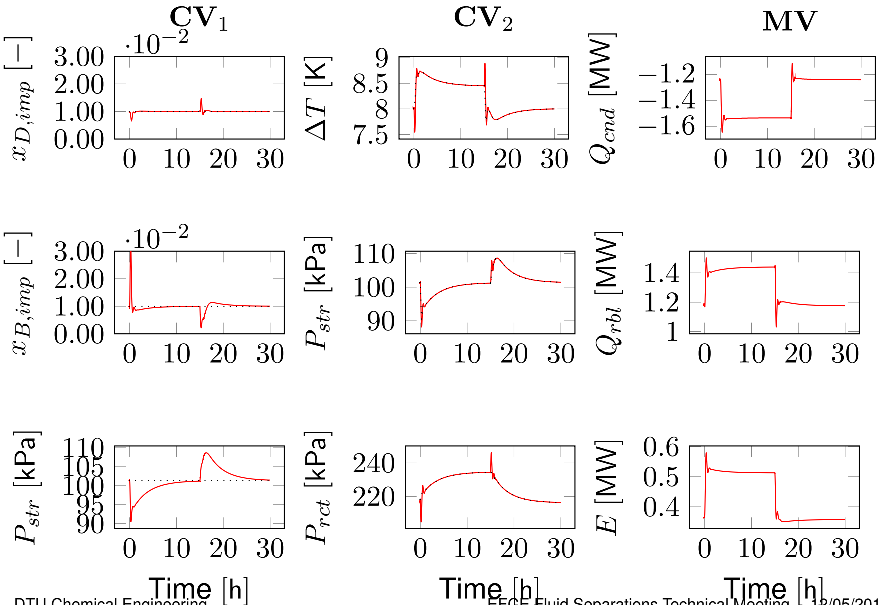


Legend:

Regulatory control layer

Supervisory control layer

Responses to +25% feed flow rate step change



Separation and Design Formulation

- Multicomponent mixture of aromatics[7]:
  - C7 fraction: 0.5% (toluene)
  - C8 fraction: 60.5% (ethylbenzene, p-xylene, m-xylene, o-xylene)
  - C9 fraction: 39.0% (cumene, n-propylbenzene, m-ethyltoluene, 1,2,3-trimethylbenzene)
- Desired:
  - $\leq$ 0.7% C9 in top
  - $\leq$ 1.5% C8 in bottoms
- 30+25 trays
- $22.6\,\mathrm{m}^2$ heat transfer area per tray
- Assume: Bottom product more valuable

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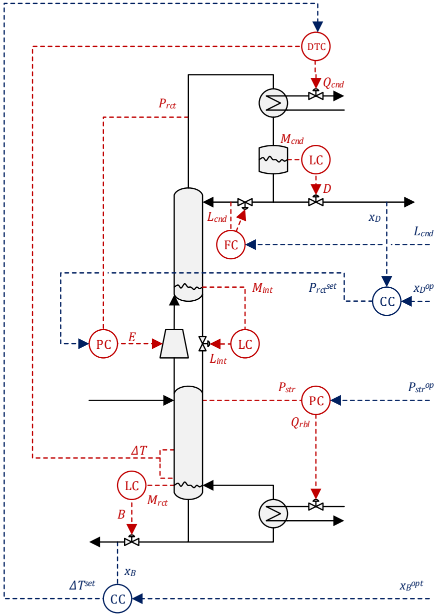
[7] T. Wakabayashi and S. Hasebe. Higher energy saving with new heat integration arrangement in heat integrated distillation column (hidic).
Proceedings of Distillation and Absorption, pages 57–63, 2014

Case Study II: Multicomponent Aromatics

Control Configuration

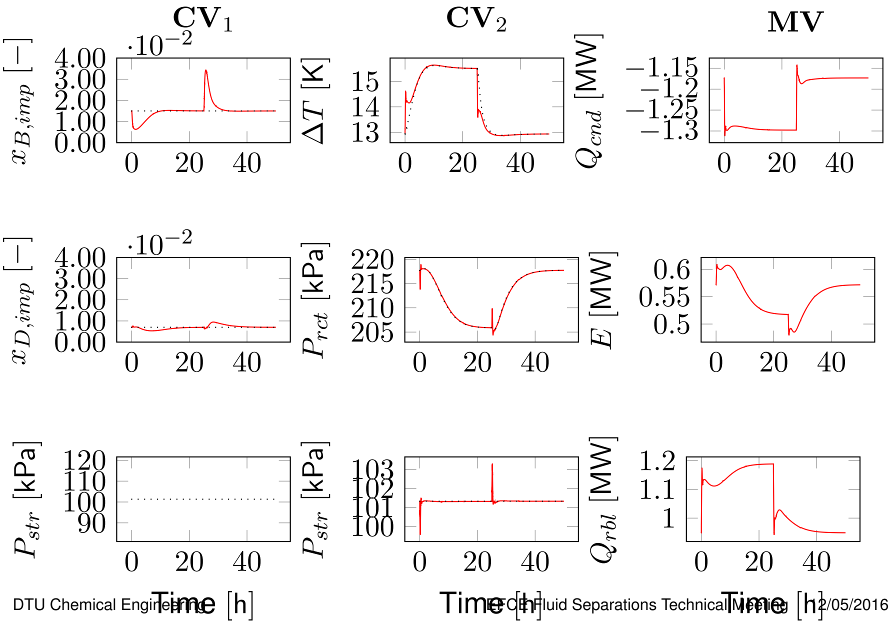


Legend:

Regulatory control layer

Supervisory control layer

Response to +10% feed C8 content step change



Conclusions

The following main conclusions can be extracted:

- Importance of regulatory control layer
- Few active constraint regions for realistic disturbance scenario
- Complex dynamic behaviour (e.g. inverse responses)
- Good performance of decentralised control
- Temperature difference control provides sufficient pressure compensation if both column section pressures are controlled

References

[1] T. Bisgaard, J.K. Huusom, and J. Abildskov. Modeling and analysis of conventional and heat-integrated distillation columns. *AIChE Journal*, 61(12):4251–4263, 2015.

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