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Practical Control of Dividing-Wall Columns

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Outline

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   - Stabilizing and Supervisory Control
2. Optimal Operation
3. Stabilizing Control Policies
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6. Pilot Plant Kaibel Column
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Introduction – Dividing Wall Columns

- 1949 – First patent by Wright
- 1965 – Paper by Petlyuk
- 1985 – First DWC built by BASF
- 1987 – G. Kaibel introduces 4-product DWC
- Present – More than 100 DWCs in operation worldwide (BASF more than 70)

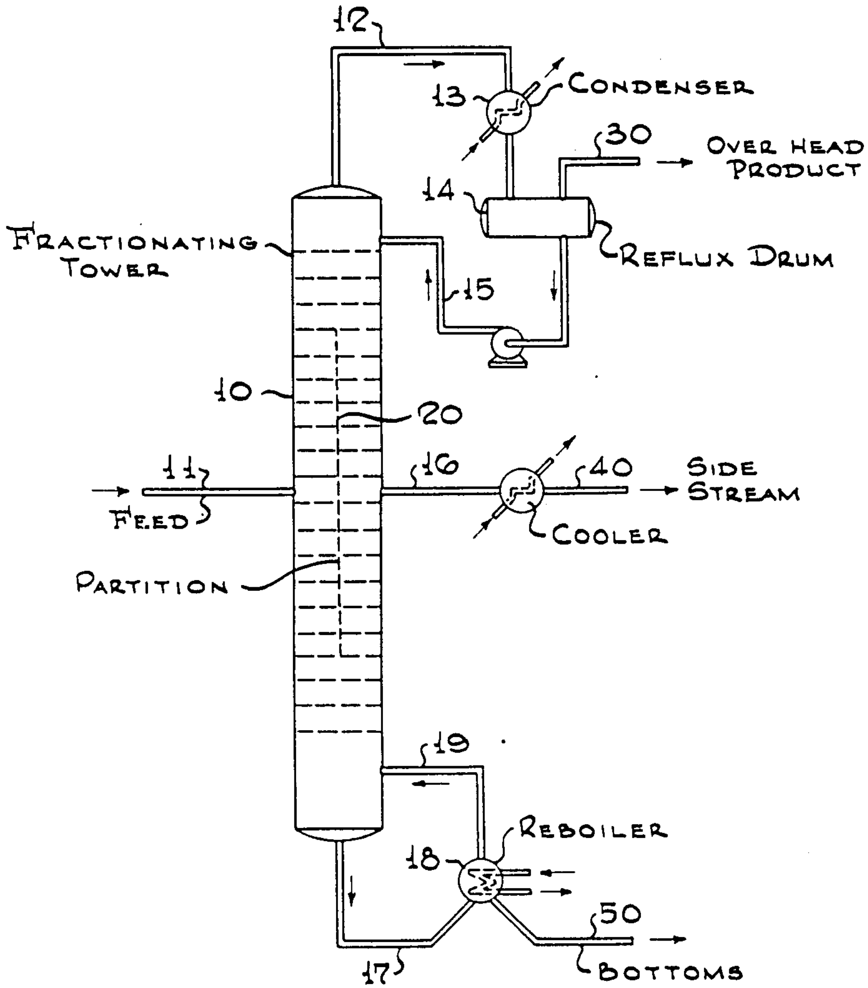
  Majority built last 10 years

  Increasing popularity due to focus on energy-saving operations and enhancments in technology

May 24, 1949. R. O. WRIGHT 2,471,134

FRACTIONATION APPARATUS

Filed July 17, 1946



F. B. Petlyuk
V. M. Platonov
D. M. Slavinskii

SOVIET UNION

Petlyuk
1965

Thermodynamically optimal method for separating multicomponent mixtures

A study of thermodynamically reversible multicomponent distillation for the selection of an optimal scheme for separating a multicomponent mixture. Mathematical description for investigation of the features of distillation with reversible mixing of streams.

THE problem of selecting the thermodynamically optimal scheme for separating a multicomponent mixture has as yet remained unsolved, although the problem has been stated by a number of authors (1—6). The approach to selecting the optimal scheme has been purely empirical and only conventional schemes for separating an n-component mixture in (n − 1) two-sectional columns have been considered. Only a study of thermodynamically reversible multicomponent distillation can ensure a scientific approach to the selection of the optimal scheme for separating a multi-component mixture.

A completely reversible process for multicomponent distillation has been described earlier (7, 8). One would naturally expect that a scheme incorporating the features of this process would be thermodynamically optimal. Several cases of such schemes with reversible mixing of the streams are proposed by the authors (see Fig. 1).

One of the fundamental properties of reversible distillation is characteristic for all of these cases: no more than one component is stripped out (exhausted) in each section (all columns are of the 1st class of fractionation). This guarantees reversibility during mixing of streams at the feed location. In cases II, IIIb, and IV, nonproductive columns do not have their

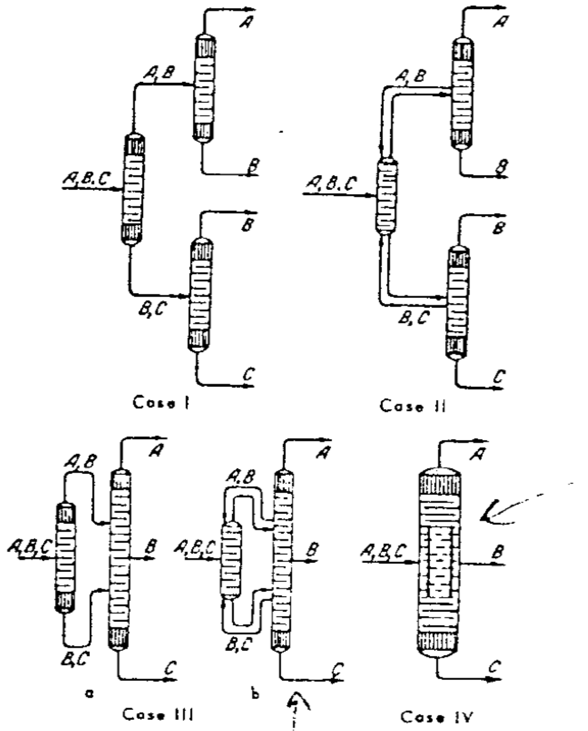


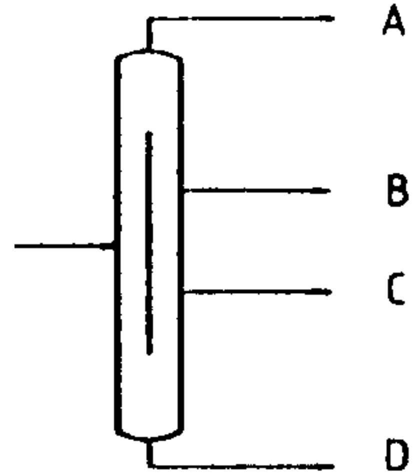
Fig. 1. Variants of a scheme with a reversible mixing of the streams.

Distillation Columns with Vertical Partitions

Gerd Kaibel * Chem. Eng. Technol. 10 (1987) 92 – 98

Distillation columns with vertical partitions can separate a feed mixture into 3 or 4 pure fractions. Compared to other column arrangements, their investment costs and energy consumption are lower. Production columns show good results and are easily controlled. Conventional distillation

However, so far, there is no indication of application on industrial scale. The reasons probably lie in the difficult numerical calculation of the complex column arrangements and a lack of experience with respect to the control behaviour.

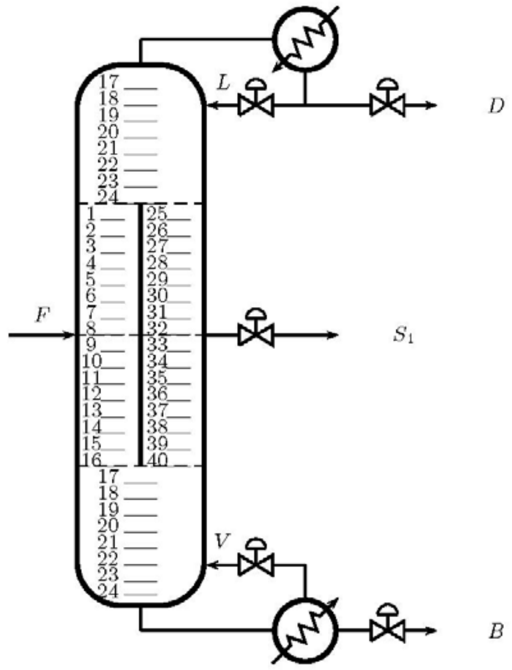


5 Control Behaviour

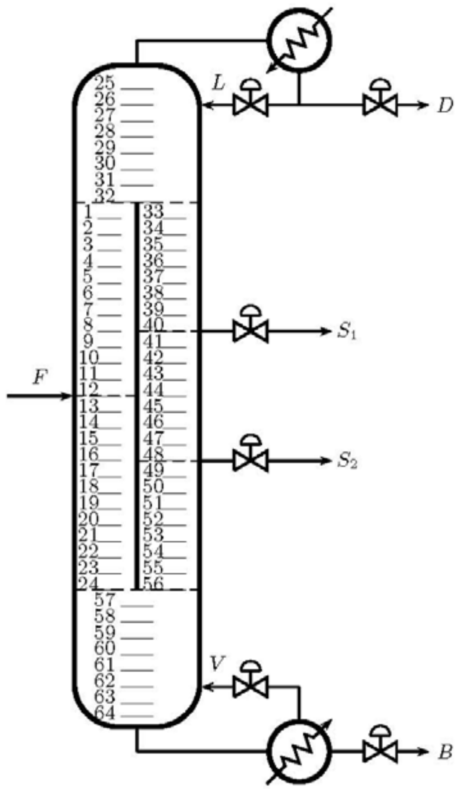
The control behaviour of a distillation column with a vertical partition corresponds to that of a conventional side outlet column. The usual control strategies can be applied.

Introduction

Dividing-Wall Column (DWC) = Fully thermally coupled column



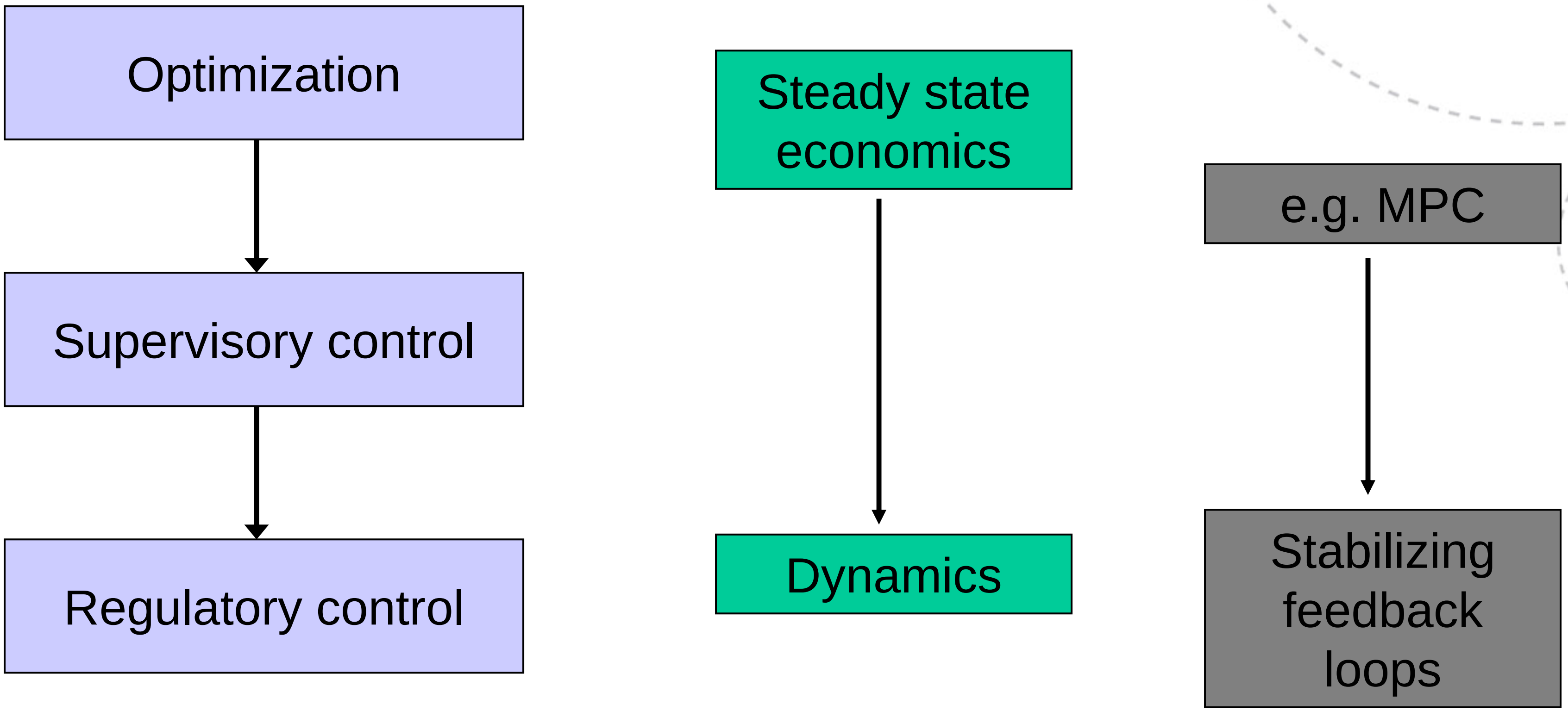
Petlyuk



Kaibel

Introduction – Control of DWCs

Control system hierarchy



Optimal Operation

General: Economic objective

Typical for DWCs: Minimize energy consumption with given product specifications

- Suitable for design and analysis

Our approach: Maximize purity of all products with a set boilup rate (normally maximum rate)

- Suitable for practical opetration – get the best out of an actual column

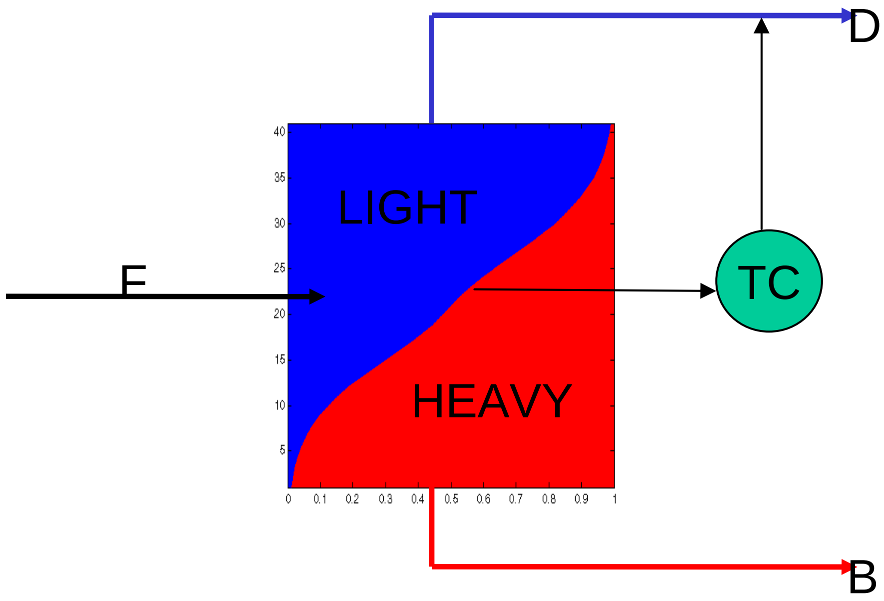
Stabilizing Control Policies

Goal: Acceptable performance using simple control policies.

Will use single temperature feedback loops to maintain ”internal splits”.

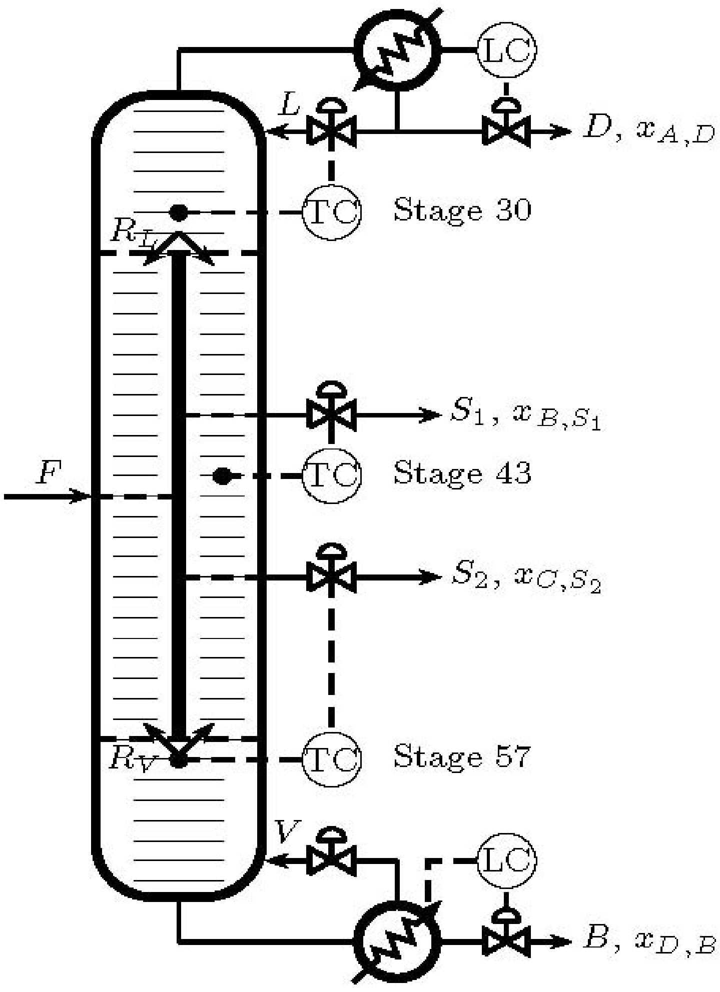
Stabilizing Control

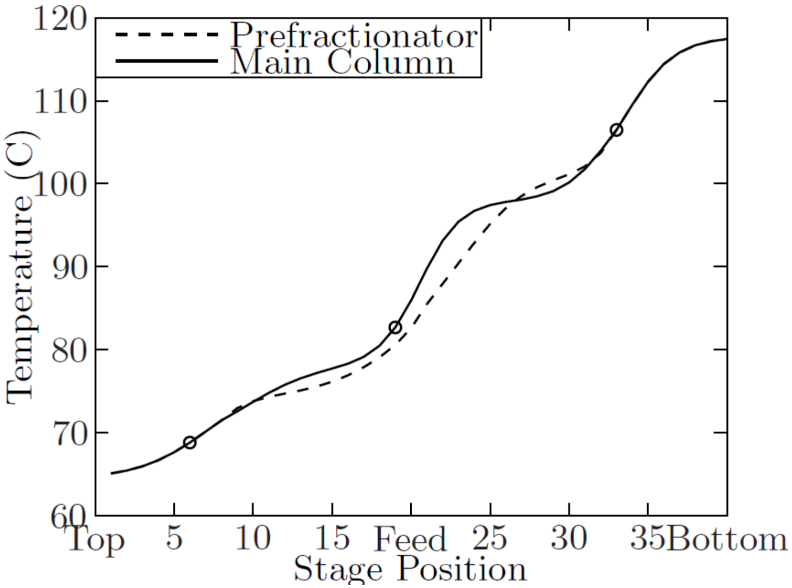
To avoid strong sensitivity to disturbances:
Temperature profile must be "stabilized"



- Must use feedback (feedforward will give drift)

Stabilizing Control based on temperatures



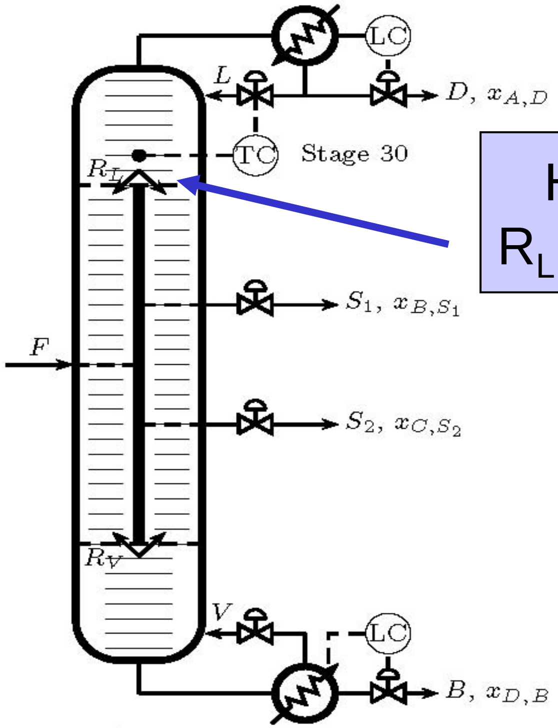


Temperature measurements have been chosen at stages with high sensitivity to inputs in the relevant column sections.

Control Configurations

1 Temperature loop

(Sidestreams kept at nominal optimum)



Here:
R_L is fixed

All cases:
F, V and R_V are fixed

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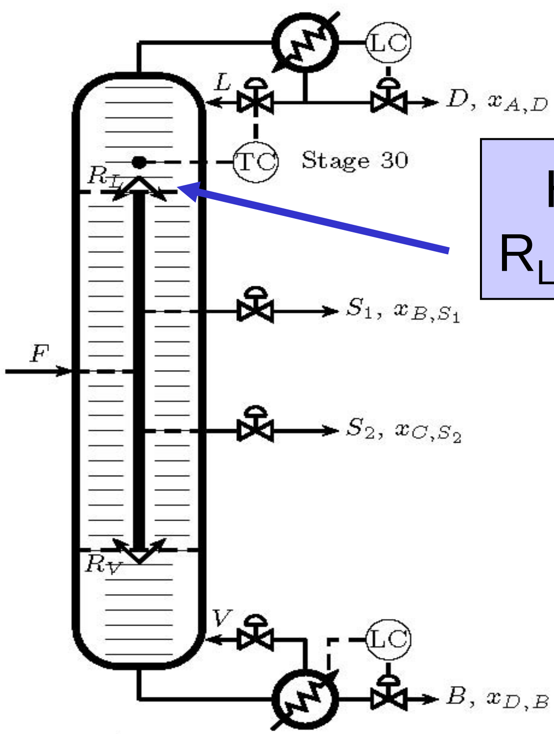
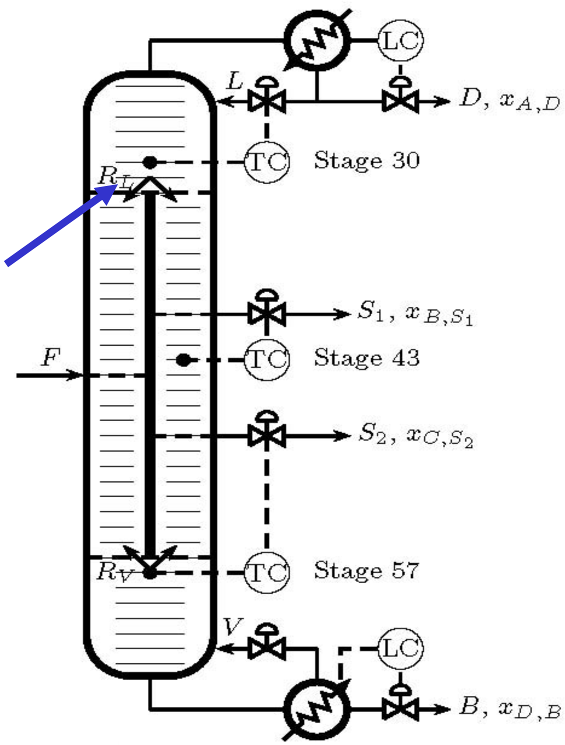
Control Configurations

1 Temperature loop

(Sidestreams kept at nominal optimum)



3 Temperature loops



Here:
R_L is fixed

All cases:
F, V and R_V are fixed

Stabilizing Control

Effect of disturbances

1 Temperature loop

	Nominal	ΔF_{+10}	$\Delta z_{B,F,+20}$	$\Delta R_{V,+10}$	$\Delta R_{V,+50}$
F	1.0000	1.1000	1.0000	1.0000	1.0000
$z_{B,F}$	0.2500	0.2500	0.3000	0.2500	0.2500
V	3.0000	3.0000	3.0000	3.0000	3.0000
R_L	0.2572	0.2572	0.2572	0.2572	0.2572
R_V	0.3770	0.3770	0.3770	0.4147	0.5655
L	2.8492	2.8330	2.8493	2.8520	2.8764
$S1$	0.2494	0.2494	0.2494	0.2494	0.2494
$S2$	0.2497	0.2497	0.2497	0.2497	0.2497
D	0.2508	0.2770	0.2507	0.2480	0.2236
B	0.2501	0.3239	0.2502	0.2529	0.2773
$x_{A,D}$	0.9703	0.9692	0.9703	0.9723	0.9813
x_{B,S_1}	0.9361	0.9586	0.9658	0.8642	0.4993
x_{C,S_2}	0.9589	0.8896	0.7925	0.8883	0.4963
$x_{D,B}$	0.9949	0.8485	0.7989	0.9875	0.8820
J	0.0349	0.0955	0.1181	0.0718	0.2876
L_{nom} (%)	-	174	238	106	724
L_{opt} (%)	-	137	199	105	675

3 Temperature loops

	Nominal	ΔF_{+10}	$\Delta z_{B,F,+20}$	$\Delta R_{V,+10}$	$\Delta R_{V,+50}$
F	1.0000	1.1000	1.0000	1.0000	1.0000
$z_{B,F}$	0.2500	0.2500	0.3000	0.2500	0.2500
V	3.0000	3.0000	3.0000	3.0000	3.0000
R_L	0.2572	0.2572	0.2572	0.2572	0.2572
R_V	0.3770	0.3770	0.3770	0.4147	0.5655
L	2.8492	2.8492	2.8502	2.8502	2.8636
$S1$	0.2494	0.2494	0.2968	0.2968	0.0705
$S2$	0.2497	0.2497	0.2541	0.2541	0.4483
D	0.2508	0.2508	0.2498	0.2498	0.2364
B	0.2501	0.2501	0.1994	0.1994	0.2447
$x_{A,D}$	0.9703	0.9692	0.9704	0.9723	0.9812
x_{B,S_1}	0.9361	0.9364	0.9363	0.8510	0.4594
x_{C,S_2}	0.9589	0.9426	0.9362	0.9444	0.4963
$x_{D,B}$	0.9949	0.9952	0.9962	0.9947	0.9951
J	0.0349	0.0430	0.0433	0.0614	0.2696
L_{nom}(%)	-	23.2	24.1	75.9	672
L_{opt}(%)	-	6.7	9.6	75.4	627

Liquid split have been kept fixed

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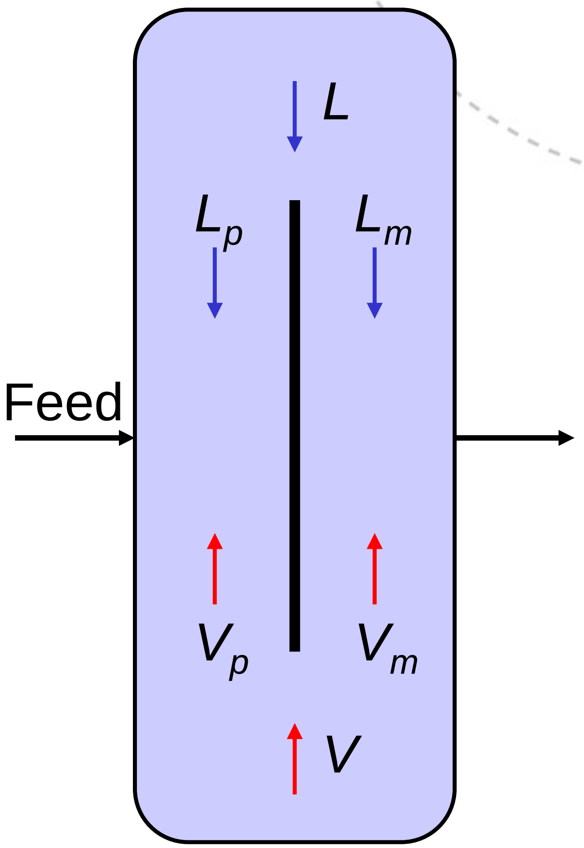
Sensitivity to Liquid Split

Key elements to DWCs:
- Liquid split
- Vapor split

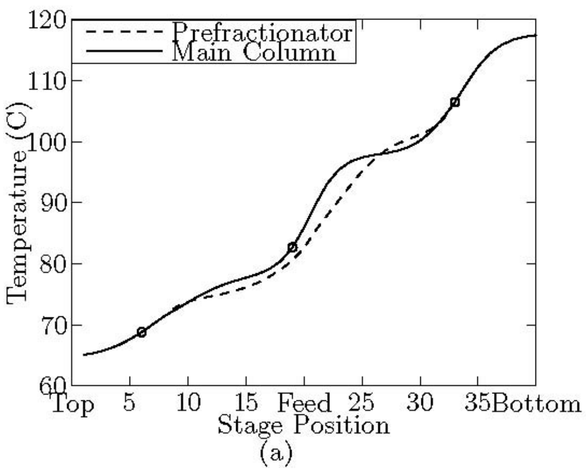
$R_L = L_p / L$
$R_V = V_p / V$

What happens when liquid split not properly adjusted?

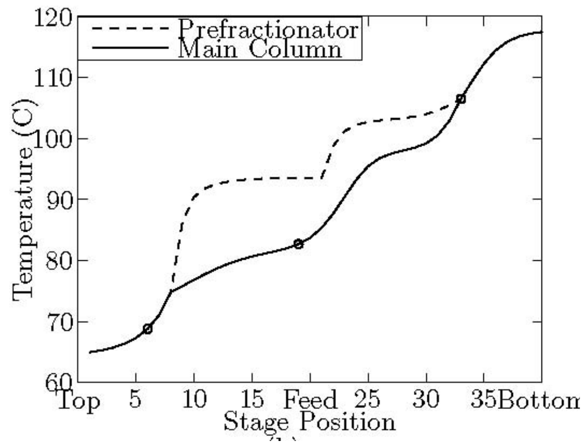


Sensitivity to Liquid Split

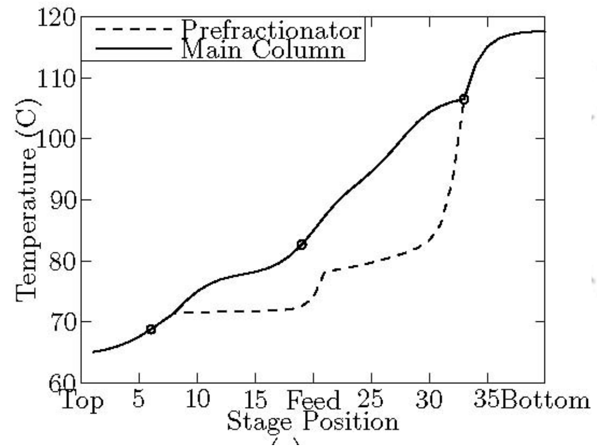
Optimal profile



R_L too low



R_L too high



3 temperature loops closed

○ Controlled temperatures

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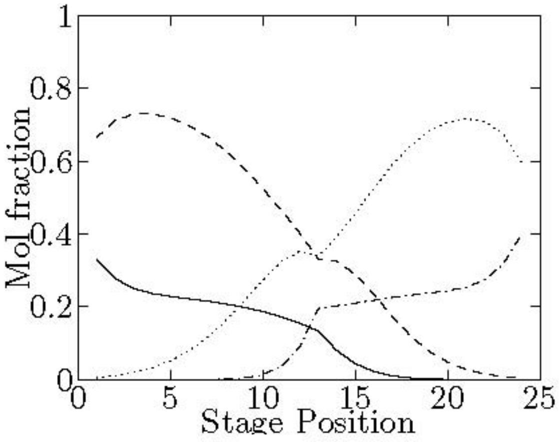
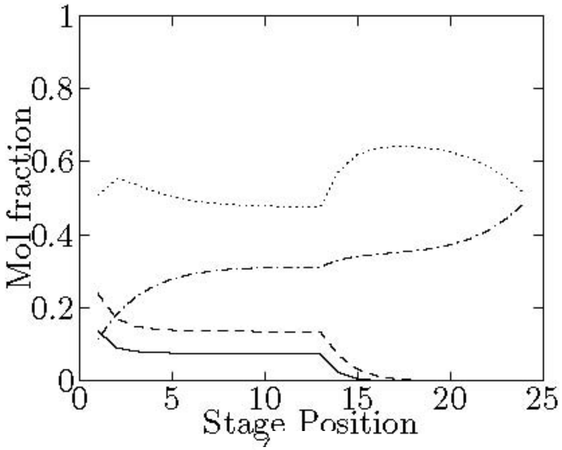
Sensitivity to Liquid Split

Prefractionator composition profiles

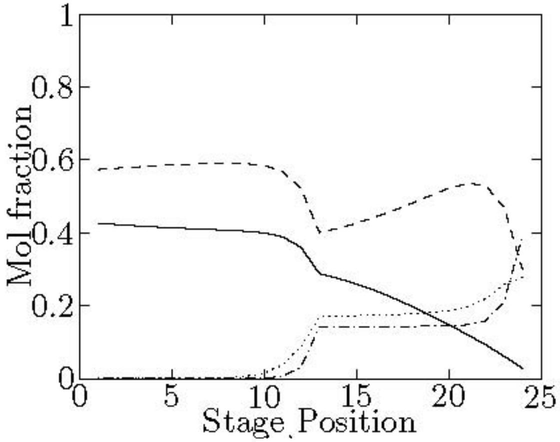
Optimal profile



R_L too low



R_L too high



3 temperature loops closed

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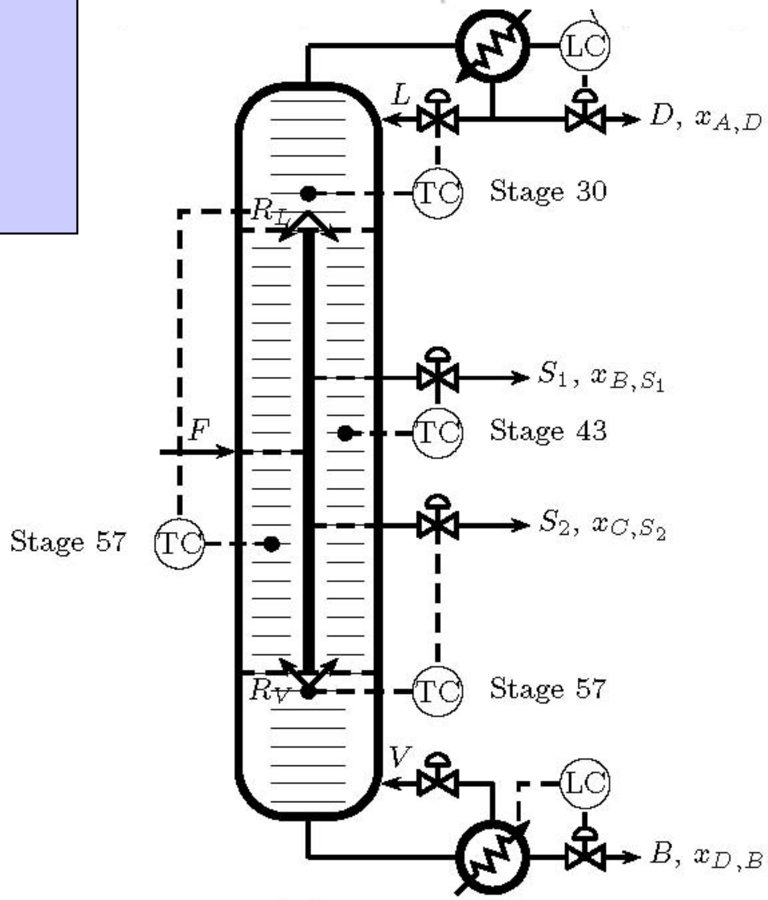
Stabilizing Control

Need to adjust liquid split online in order to stabilize prefractionator

Adding new temperature loop



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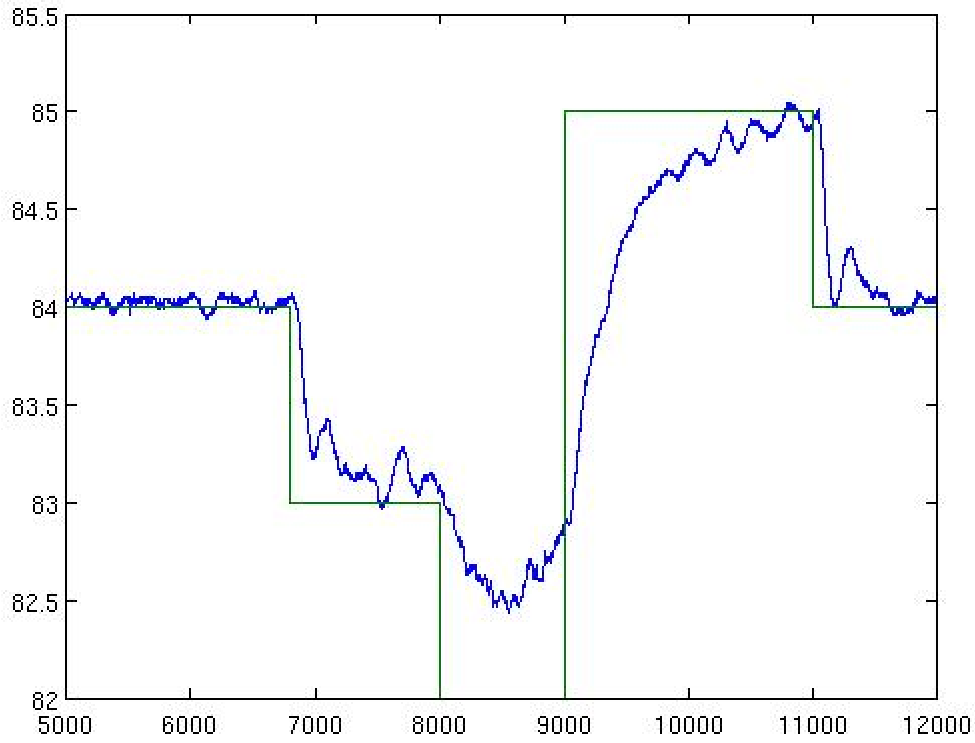
Step response test on pilot column

Prefractionator temperature below feed controlled by adjusting the liquid split



Stabilizing Control

4 Temperature loops

	Nominal	ΔF_{+10}	$\Delta z_{B,F,+20}$	$\Delta R_{V,+10}$	$\Delta R_{V,+50}$
F	1.0000	1.1000	1.0000	1.0000	1.0000
$z_{B,F}$	0.2500	0.2500	0.3000	0.2500	0.2500
V	3.0000	3.0000	3.0000	3.0000	3.0000
R_L	0.2572	0.2434	0.2371	0.2969	0.4549
R_V	0.3770	0.3770	0.3770	0.4147	0.5655
L	2.8492	2.8349	2.8528	2.8496	2.8532
$S1$	0.2494	0.2746	0.3032	0.2498	0.2532
$S2$	0.2497	0.2753	0.2500	0.2499	0.2510
D	0.2508	0.2751	0.2472	0.2504	0.2468
B	0.2501	0.2750	0.1996	0.2499	0.2491
$x_{A,D}$	0.9703	0.9694	0.9706	0.9703	0.9705
x_{B,S_1}	0.9361	0.9324	0.9315	0.9354	0.9254
x_{C,S_2}	0.9589	0.9562	0.9535	0.9590	0.9580
$x_{D,B}$	0.9949	0.9945	0.9958	0.9949	0.9950
J	0.0349	0.0406	0.0405	0.0351	0.0380
L_{nom} (%)	-	16	16	0.6	8.9
L_{opt} (%)	-	0.7	2.5	0.3	2.4

Temperature controller adjusts for a very faulty vapor split

Summary three configurations

	1 loop		3 loops		4 loops	
	J $\left[\frac{mol}{min}\right]$	L_{nom} [%]	J $\left[\frac{mol}{min}\right]$	L_{nom} [%]	J $\left[\frac{mol}{min}\right]$	L_{nom} [%]
Nominal	0.0349	-	0.0349	-	0.0349	-
$\Delta R_L = -50\%$	0.1626	366	0.1332	282	0.0349	0*
$\Delta R_L = -25\%$	0.0932	167	0.0769	120	0.0349	0*
$\Delta R_L = +25\%$	0.0657	88	0.0576	65	0.0349	0*
$\Delta R_L = +50\%$	0.1027	194	0.1113	219	0.0349	0*
$\Delta F = +10\%$	0.0955	174	0.0430	23	0.0406	16
$\Delta z_{B,F} = +20\%$	0.1181	238	0.0433	24	0.0405	16
$\Delta R_V = +10\%$	0.0718	106	0.0614	76	0.0351	0.6
$\Delta R_V = +50\%$	0.2876	724	0.2696	672	0.0380	8.9

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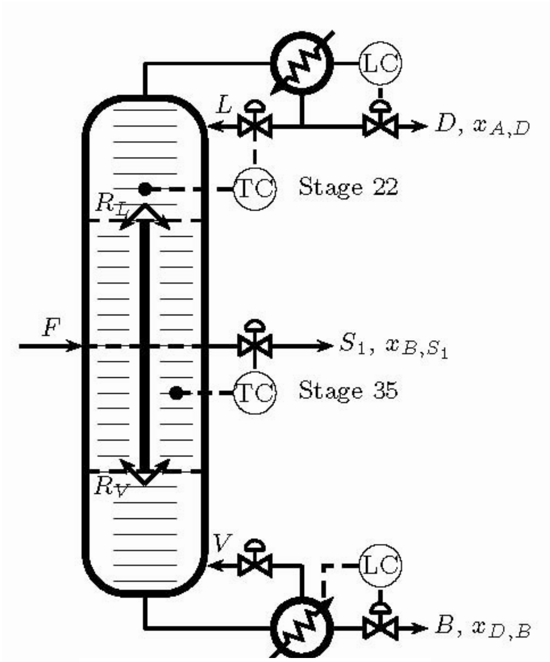
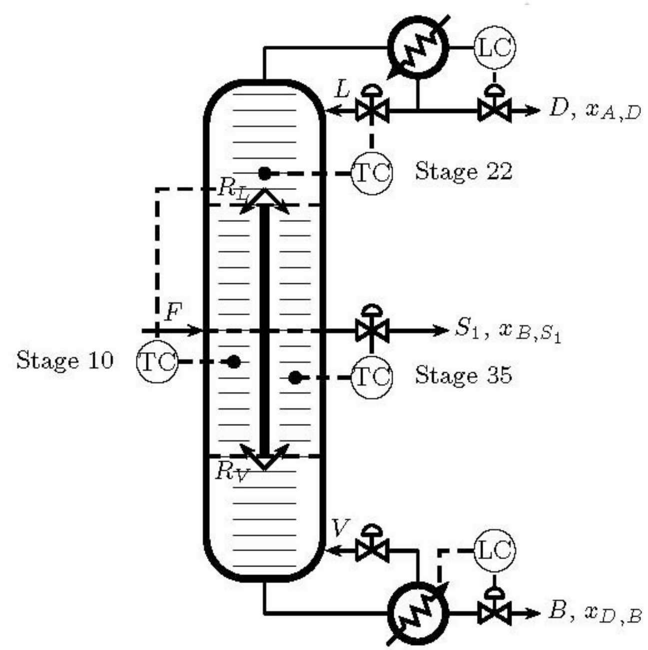
Petlyuk column control configurations:



2 Temperature loops



3 Temperature loops
- including liquid split

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Stabilizing Control

Summary three configurations Petlyuk column

	1 loop		2 loops		3 loops	
	J $[\frac{mol}{min}]$	L_{nom} [%]	J $[\frac{mol}{min}]$	L_{nom} [%]	J $[\frac{mol}{min}]$	L_{nom} [%]
Nominal	0.0215	-	0.0215	-	0.0215	-
$\Delta R_L = -50\%$	0.1322	515	0.0833	287	0.0215	0
$\Delta R_L = -25\%$	0.0552	157	0.0388	81	0.0215	0
$\Delta R_L = +25\%$	0.0352	64	0.0367	71	0.0215	0
$\Delta R_L = +50\%$	0.0765	256	0.0834	288	0.0215	0
$\Delta F = +10\%$	0.0550	156	0.0331	54	0.0355	65
$\Delta z_{B,F} = +20\%$	0.0824	283	0.0263	22	0.0382	78
$\Delta R_V = +10\%$	0.0411	91	0.0314	46	0.0240	12
$\Delta R_V = +50\%$	0.3127	1350	0.2735	1170	0.1494	595

Summary three configurations High-purity Petlyuk column (twice no. of stages)

	1 loop		2 loops		3 loops	
	J $[\frac{mol}{min}]$	L_{nom} [%]	J $[\frac{mol}{min}]$	L_{nom} [%]	J $[\frac{mol}{min}]$	L_{nom} [%]
Nominal	0.0006	-	0.0006	-	0.0006	-
$\Delta R_L = -50\%$	0.1513	24000	0.0843	13500	0.0006	0
$\Delta R_L = -25\%$	0.0524	8300	0.0279	4400	0.0006	0
$\Delta R_L = +25\%$	0.0071	1000	0.0263	4100	0.0006	0
$\Delta R_L = +50\%$	0.0684	11000	0.0947	15000	0.0006	0
$\Delta F = +10\%$	0.0341	5600	0.0021	250	0.0016	170
$\Delta z_{B,F} = +20\%$	0.0671	11000	0.0017	180	0.0012	120
$\Delta R_V = +10\%$	0.0463	7600	0.0237	3900	0.0008	30
$\Delta R_V = +50\%$	0.2901	48000	0.2038	34000	0.1081	18000

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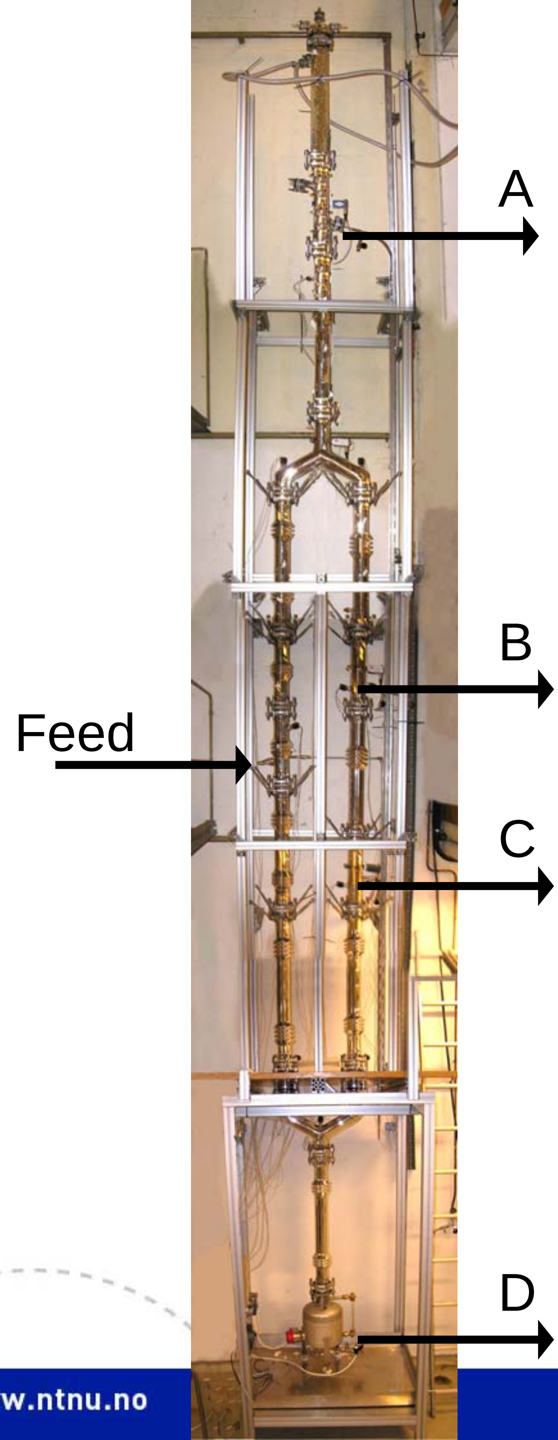
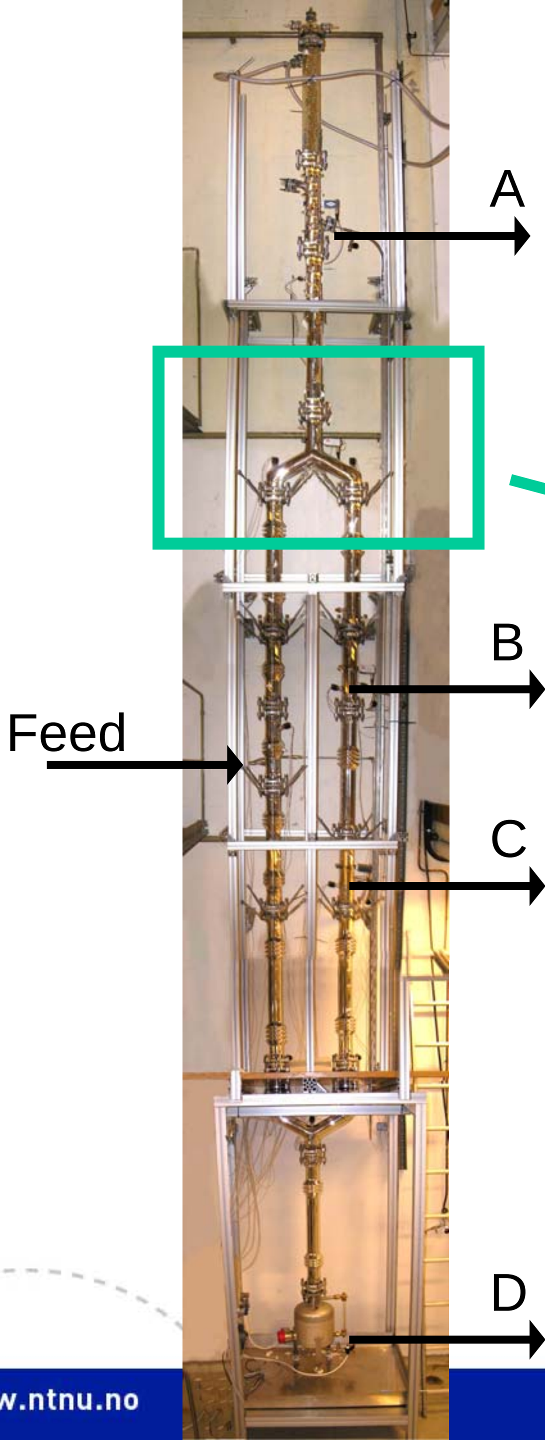
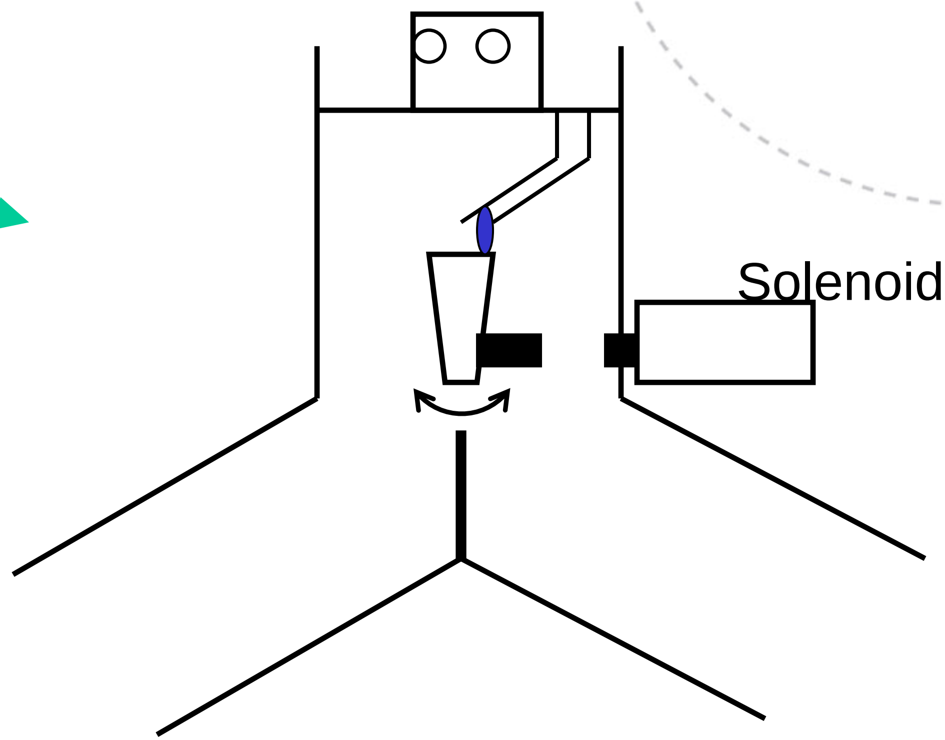
Pilot Plant Kaibel Column



- Vacuum-jacketed glass.
- 5 cm internal diameter.
- 8 meters tall.
- 3 kW reboiler.
- Packing: glass Raschig rings

Manipulation of liquid-split





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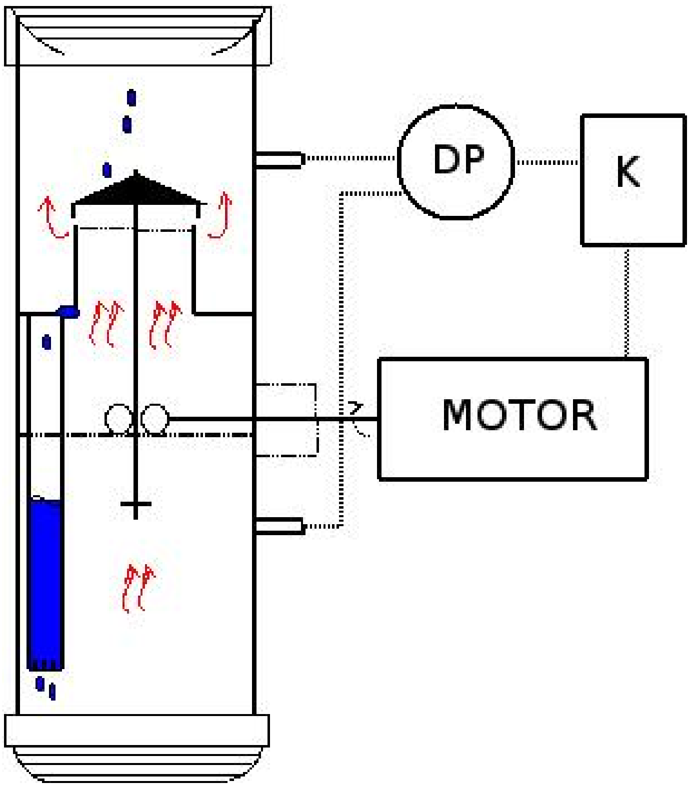
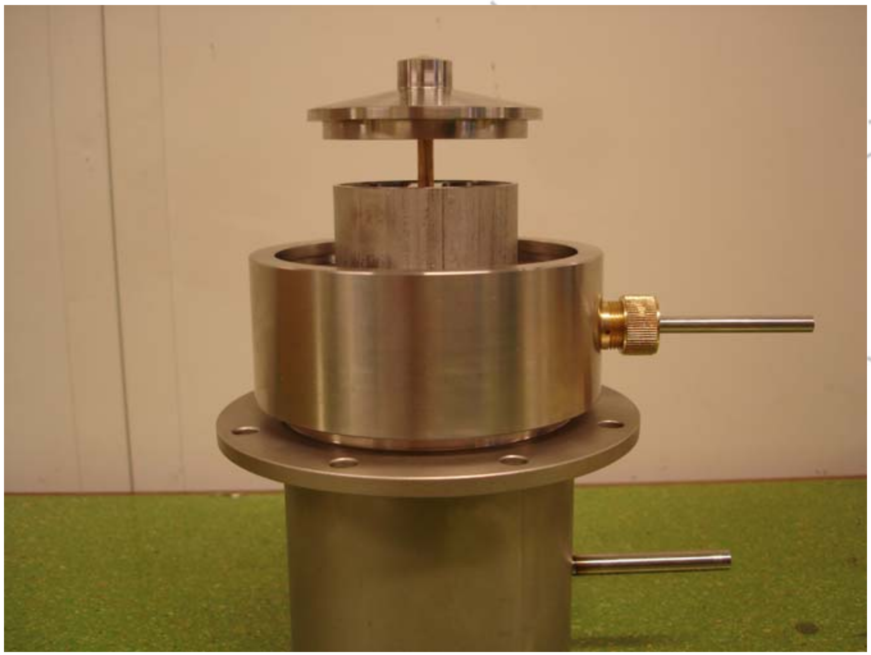
Manipulation of vapor-split





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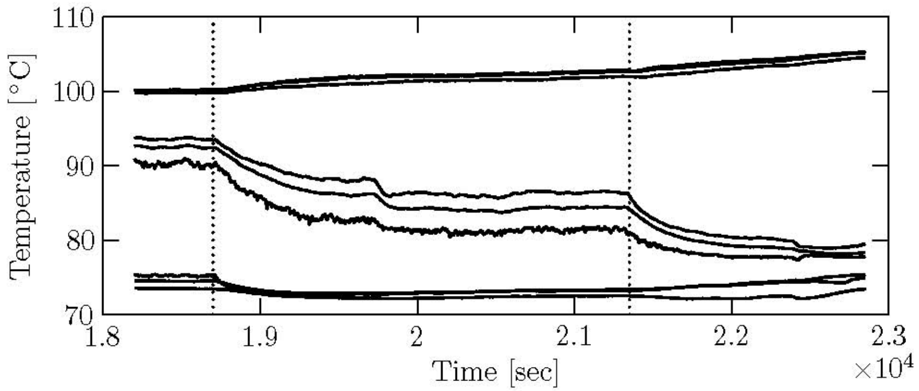
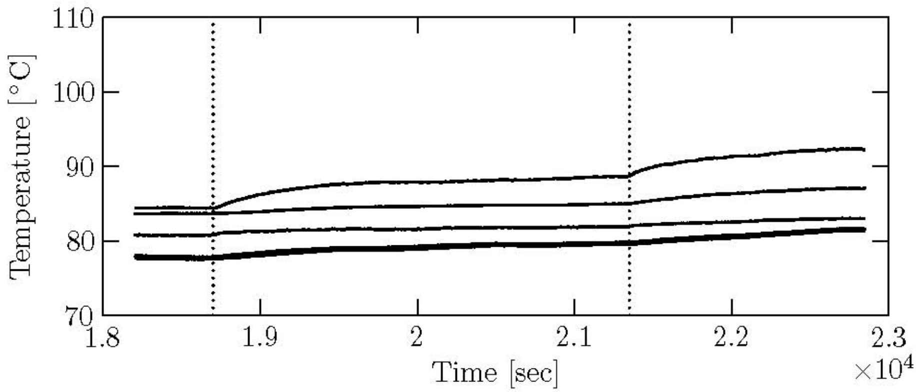
Manipulation of vapor-split



(a) Temperatures on main column side of partition



(b) Temperatures on prefractionator side of partition

Responses to step-changes in R_V

R_V increased at 18700s and again at 21300s

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Conclusions

- Introduced an approach to practical Optimal Operation of DWC's
- Focused on achieving acceptable perfomance using only temperature controllers
- Using liquid split actively in control is key rejecting disturbances. – Can counteract incorrectly set vapor distribution

Thank you for your attention!