UNIVERSITAT POLITÈCNICA DE CATALUNYA

Department of Chemical Engineering

ENERGY OPTIMISATION AND CONTROLLABILITY IN COMPLEX DISTILLATION COLUMNS

Autor: Maria Serra i Prat
Director: Miquel Perrier

Barcelona, june 2000

NOMENCLATURA

A: A feed flowrate

$\boldsymbol{A}$: state-space matrix

B: B feed flowrate

B: bottoms flowrate

$\boldsymbol{B}$: state-space matrix

$B1$: bottoms flowrate in upstream column

$B2$: bottoms flowrate in downstream column or COL2

$B3$: bottoms flowrate in COL3

$B4$: net flow down section 4 in the DWC

BS: bottoms flowrate in stripper

$\boldsymbol{B_n}$ and $\boldsymbol{B_p}$: DMC linear model matrix

C: C feed flowrate

$\boldsymbol{C}$: state-space matrix

d: feedback variable for optimising control

d: delay

d: disturbance variable

D: distillate flowrate

$\boldsymbol{D}$: state-space matrix

$D1$: distillate in upstream column

$D2$: distillate in downstream column or COL2

$D3$: distillate in COL3

DR: distillate in rectifier

DTS: feedback variable for optimising control

e: error in DMC

ESI: Ease of Separation Index

F: feed flowrate

F_{BLT}: BLT detuning factor

$\boldsymbol{G}$: transfer function

$\boldsymbol{G}_{diag}$: diagonal matrix with the diagonal elements of $\boldsymbol{G}$

$\boldsymbol{G}_d$: the transfer function corresponding to the disturbances

I: reset time of the controller

k_u: ultimate gain

K: steady state gain

$\boldsymbol{K}$: controller transfer function

K_c: controller gain

l: liquid flowrate

$l0$: nominal liquid flowrate

L: reflux

LI: reflux of the first column

LII: reflux of the second column

LIQ: liquid from the stripper to the main column

LM: reflux of the main column

LR: reflux in the rectifier

L_{CM}: multivariable closed-loop log modulus

L_f: liquid flowrate from the main column to the prefractionator top in the Petlyuk Column

m: control horizon in DMC

M: holdup

$M0$: nominal holdup

MRR: minimum reflux ratio

n: number of components

n: identification horizon in DMC

NCB: last common tray before the wall in a DWC

NCD: first common tray after the wall in a DWC

NF: feed tray

NFI: feed tray of the first column

$NFII$: feed tray of the second column

NM: number of trays of the main column

NP: number of trays of the prefractionator

NR: number of trays of the rectifier

NS: number of trays of the stripper

NT: total number of trays

NTI: total number of trays of the first column

$NTII$: total number of trays of the second column

p: prediction horizon in DMC

P_u: period ultimate

q_F: liquid fraction in the feed

RR: reflux ratio

s: time Laplace transform

S: sidestream flowrate

$\boldsymbol{S}$: sensitivity function

$SPLITB$: split in the base of the wall in a DWC

$SPLITD$: split at the top of the wall in a DWC

t: time

$\boldsymbol{T}$: complementary sensitivity function or closed-loop transfer function

$\boldsymbol{T_i}$: closed-loop transfer function at the input

$T_{N,i}$: temperature of tray i in section N

u: input variable

$\boldsymbol{u}$: matrix of output directions in singular value decomposition

v: vapour flowrate

$v0$: nominal vapour flowrate

$\boldsymbol{v}$: matrix of input directions in singular value decomposition

V: boilup

VI: boilup of the first column

VII: boilup of the second column

VAP: vapour from the main column to the rectifier

VM: boilup of the main column

VS: boilup of the stripper

V_I: vapour flowrate to the prefractionator top to the main column in the Petlyuk Column

w: frequency

w_B: bandwidth frequency

w_{GM} and w_{PM}: frequencies of the gain margin and the phase margin

w_i: uncertainty in the input channels

w_u: ultimate frequency

x: state variable

x_i: i liquid fraction

x_{AD}: purity of product A (molar)

x_{BS}: purity of product B (molar)

x_{CB}: purity of product C (molar)

x_B^l: B liquid composition in the tray of the Petlyuk Column main column connected to the prefractionator top

x^b_A: feedback variable for optimising control

y: output variable

y_i: i vapour fraction

y_B^l: B vapour composition at the top of the prefractionator in the Petlyuk Column

y^d_C: feedack variable for optimising control

z_i: feed composition of component i

α_i: relative volatility of component i

α: A molar fraction in Petlyuk Column B1

β: B molar fraction in the Petlyuk Column prefractionator distillate

ΔN and $\Delta N'$: feedback variable for optimising control

Δt: sampling interval in DMC

θ: root of the Underwood equation

λ: move suppression factor in DMC

σ: matrix of singular values in singular value decomposition

τ: time constant of the liquid flow dynamics

τ_p: open-loop time constant

τ_c: time constant of the controller

ABBREVIATIONS

BLT: Biggest Log-modulus Tuning

CLDG: Closed Loop Disturbance Gain

CN: Condition Number

DMC: Dynamic Matrix Control

DOF: Degrees Of Freedom

DWC: Divided Wall Column

GM: Gain Margin

II: Intersivity Index

MIMO: Multiple Input Multiple Output

MPC: Model Predictive Control

MRI: Morari Resiliency Index

PI: Proportional Integral (controller)

PM: Phase Margin

PRGA: Performance Relative Gain Array

RDG: Relative Disturbance Gain

RGA: Relative Gain Array

SISO: Single Input Single Output

REFERENCES

Abdul Mutalib, M. I. & Smith, R. 1998. Operation and control of Dividing Wall Distillation Columns. *Trans IChemE*, 76, Part A, 308-318.

Agrawal, R. & Fidkowski, Z. T. 1996. On the Use of Intermediate Reboilers in the Rectifying Section and Condensers in the Stripping Section of a Distillation Column. *Ind. Eng. Chem. Res.*, 35.

Agrawal, R. & Fidkowski, Z. T. 1998 a. More Operable Arrangements of Fully Thermally Coupled Distillation Columns, *AIChEJ*, 44, 11.

Agrawal, R. & Fidkowski, Z. T. 1998 b. Are Thermally Coupled Distillation Columns Always Thermodynamically More Efficient for Ternary Separations? *Ind. Eng. Chem. Res.*, 37, 3444-3454.

Agrawal, R. & Fidkowski, Z. 1999. New thermally coupled schemes for ternary distillations. *AIChEJ*, 45, 3, 485-496.

Alatiqi, I. M. & Luyben, W. L. 1985. Alternative Distillation Configurations for Separating Ternary Mixtures with Small Concentrations of Intermediate in the Feed. *Ind. Eng. Chem. Process Des. Dev.*, 24, 500-506.

Alatiqi, I. M. & Luyben, W. L. 1986. Control of a Complex Sidestream Column/Stripper Distillation Configuration. *Ind. Eng. Chem. Process Des. Dev.*, 25, 762-767.

Annakou, O. & Mizsey, P. 1996 a. Rigorous Comparative Study of Energy-Integrated Distillation Schemes. *Ind. Eng. Chem. Res.*, 35, 1877-1885.

Annakou, O.; Meszaros, A.; Fonyo, Z. & Mizsey, P. 1996 b. Operability Investigation of Energy Integrated Distillation Schemes. *Hungarian Journal of Industrial Chemistry.*, 24, 155-160.

Carlberg, N. A. & Westerberg, A. W. 1989. Temperature-Heat Diagrams for Complex Columns. 3. Underwood's Method for the Petlyuk Configuration. *Ind. Eng. Chem. Res.*,28 ,9

Cheng, H-C. & Luyben, W. L. 1985. Heat-integrated Distillation Columns for Ternary Separations. *Ind. Eng. Chem. Process Des. Dev.*, 24, 3.

Christiansen, A. C. 1997. Studies on Optimal Design and Operation of Integrated Distillation Arrangements. Ph.D.

Doukas, N. & Luyben, W. L. 1978 a. Economics of Alternative Distillation Configurations for the Separation of Ternary Mixtures. *Ind. Eng. Chem. Process Des. Dev.*, 17, 3, 272-281.

Doukas, N. & Luyben, W. L. 1978 b. Control of Sidestream Columns Separating Ternary Mixtures. Inst. Tech., 25, 43.

Doukas N. P. & Luyben W. L. 1981. Control of an Energy-Conserving Prefractionator/Sidestream Column Distillation System. Ind. Eng. Chem. Process. Des. Dev., 20, 147-153.

Dunnebier G. & Constantinos C. Pantelides. 1999. Optimal Design of Thermally Coupled Distillation Columns. *Ind. Eng. Chem. Res.*, 38, 162-176.

Fidowski, Z.; Krolikowski, L. 1986. Thermally Coupled System of Distillation Columns: Optimisation Procedure. *AIChE J.*, 32, 4, 537-546.

Fidkowski, Z.; Krolikowski, L. 1987. Minimum Energy Requirements of Thermally Coupled Distillation Systems. *AIChEJ*, 33, 4, 643-653.

Fidkowski, Z. & Krolikowski, L. 1990. Energy Requirements of Nonconventional Distillation Systems. *AIChEJ*, 36, 8, 1275-1278.

Finn, A. J. 1993. Consider Thermally Coupled Distillation. *Chemical Engineering and Progress.*

Georgiou, A.; Georgakis, C. & Luyben, W. L. 1988. Nonlinear Dynamic Matrix Control for High-Purity Distillation Columns. *AIChEJ*, 34, 8, 1287-1298.

Glinos, K. N. & Malone, M. F. 1985. Design of Sidestream Distillation Columns. *Ind. Eng. Chem. Process Des. Dev.,* 24, 822-828.

Glinos, K & Malone, M. F. 1988. Optimality regions for Complex Column Alternatives in Distillation Systems. *Chem. Eng. Res. Des.*, 66, 229-240.

Halvorsen, I. J. & Skogestad, S. 1997. Optimising Control of Petlyuk Distillation: Understanding the Steady-State Behaviour. *Computers chem. Engng.*, 21, Suppl. s249-s254.

Halvorsen, I. J. & Skogestad, S. 1999. Optimal Operation of Petlyuk Distillation: Steady-State Behviour. *Journal of Process Control*, 9, 407-424.

Hernandez, S. & Jimenez, A. 1999. Controllability Analysis of Thermally Coupled Distillation Systems. *Ind. Eng. Chem. Res.*, 38, 3957-3963.

Kaibel, G. 1987. Distillation Columns with Vertical Partitions. *Chem. Eng. Thecnol.*, 10, 92-98.

Kaibel, G.; Blass, E. & Kohler, J. 1990. Thermodynamics-guideline for the Development of Distillation Column Arrangements. Gas Separation & Purification, 4,109-114.

King, C. J. 1981 (second edition). Separation Processes. McGraw-Hill Book Company. New York.

Luyben, W. L. 1990. Process Modeling, Simulation, and Control for Chemical Engineers. McGraw-Hill Publishing Company, New York.

Luyben, W.L. 1992. Practical Distillation Control. Van Nostrand Reinhold, New York.

Luyben, W. L.; Tyreus, B. D. & . Luyben, M. L. 1998. Plantwide Process Control.

Marlin, T. E. 1995. Process Control. Design Processes and Control Systems for Dynamic Performance. McGraw-Hill, Inc. New York.

MATLAB, 1998. The MathWorks inc.

McCabe, W. L.; Smith, J. C.; Harriot, P. 1985 (Fourth edition). Unit Operations of Chemical Engineering. McGraw-Hill Book Company. New York.

McIntosh, A. R.; Shah, S. L. & Fisher, D. G. 1991. Analysis and Tuning of Adaptive Centralised Predictive Control. *The Canadian Journal of Chemical Engineering*, 1, 97-110.

Morari, M. & Zafirou, E. 1989. Robust Process Control. Prentice Hall, Englewood Cliffs, New Jersey.

Ogunnaike, B. A. & Ray, W. H. 1994. Process Dynamics, Modelling, and Control, Oxford University Press, New York.

Petlyuk, F. B.; Platonov, V. M.; Slavinskii, D. M. 1965. Thermodynamically Optimal Method for Separating Multicomponent Mixtures. *Int. Chem. Eng.*, 5, 3, 555-561.

PROII, 1994. Simulation Sciences Inc.

Shridhar, R. & Cooper, D. J. 1997. A Tuning Strategy for Unconstrained SISO Model Predictive Control. *Ind. Eng. Chem. Res.*, 36, 729-746.

Skogestad, S & Morari, M. 1988. Understanding the Dynamic Behaviour of Distillation Columns. *Ind. Eng. Chem. Research*, 27, 10, 1848-1862.

Skogestad, S.; Jacobsen, E. W. & Morari, M. 1990 a. Inadequacy of steady-state analysis for feedback control: distillate-bottom control of distillation columns. *Ind. Eng. Chem. Res.*, 29, 2339-2346.

Skogestad, S.; Lundstrom, P. & Jacobsen, E. W. 1990 b. Selecting the best distillation control configuration. *AIChEJ*, 36, 5.

Skogestad, S. & Postlethwaite, I. 1996. Multivariable Feedback Control. Analysis and Design. John Wiley & Sons. Chichester.

Skogestad, S. 1997. Dynamics and Control of Distillation Columns: A Tutorial Introduction, *Trans IchemE* Part A, 75.

Stanley, G.; Marino-Galarraga, M. & McAvoy, T. 1985. Shortcut Operability Analysis. 1. The Relative Disturbance Gain. *Ind. Eng. Chem. Process Des. Dev.*, 24, 1181, 1188.

Tedder, D. W. & Rud, D. F. 1978. Parametric Studies in Industrial Distillation: Part 1. Design Comparisons. *AIChEJ*, 24, 2, 303-315.

Triantafyllow, C.; Smith, R. 1992. The Design and Optimisation of Fully Thermally Coupled Distillation Columns. *Trans. Inst. Chem. Eng.*, 70, 118-132.

Underwood, A. J. V. 1948. Fractional Distillation of Multicomponent Mixtures. *Chem. Eng. Prog.*, 44.

Wolff, E. A. & Skogestad, S. 1995. Operation of Integrated Three-Product (Petlyuk) Distillation Columns. *Ind. Eng. Chem. Res.*, 34, 2094-2103.

Wright, R. O. U. S. Patent 2, 471, 134, May 24, 1949.