Application of the New FRI Valve Tray Efficiency Model in Column Simulation and Design

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Special thanks to FRI

Mike Resetarits
Anand Vennavelli

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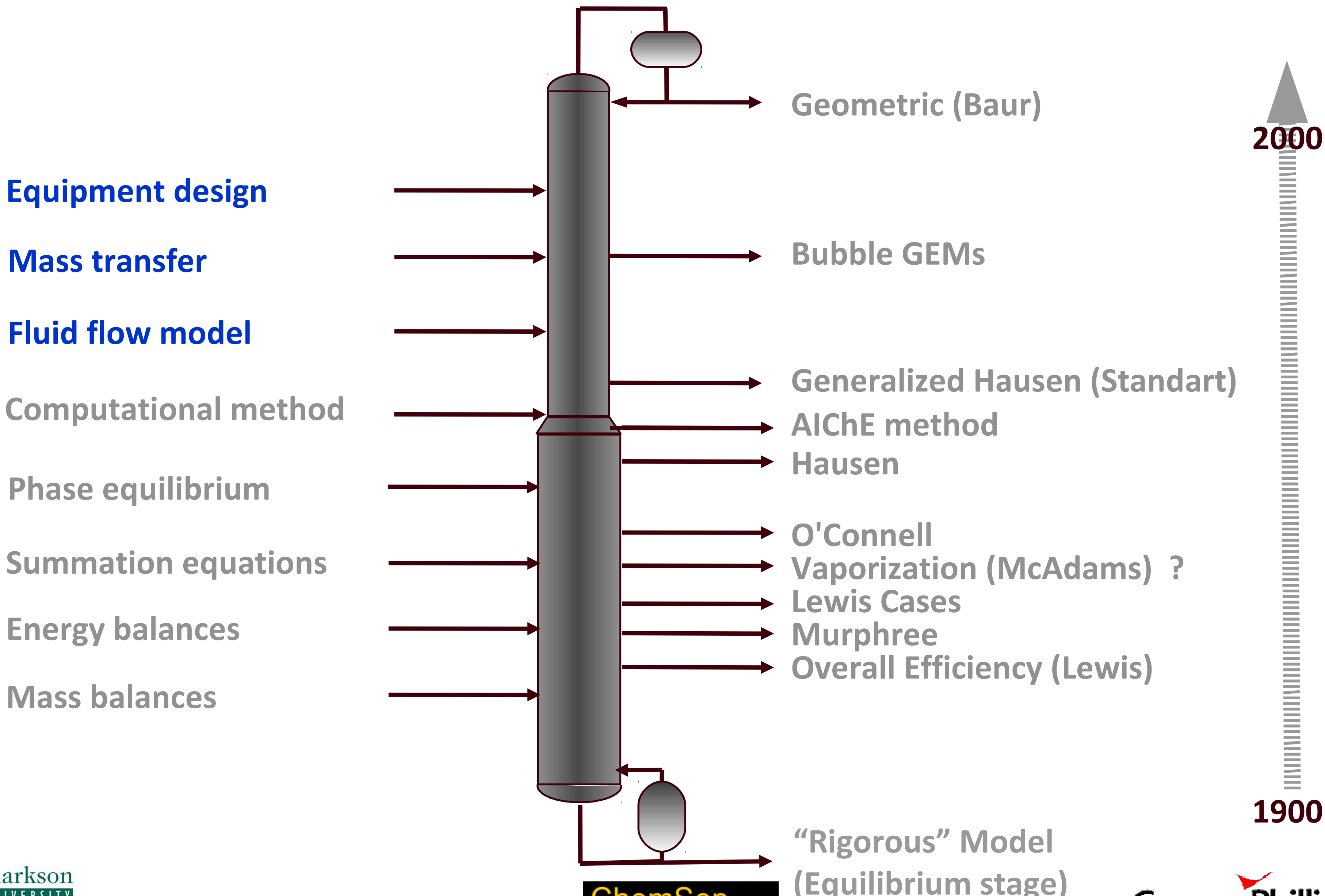
This Presentation:

1. **Background – Efficiency concepts through the years**
2. **Bubble Geometry Efficiency Models (Bubble GEMs)**
3. **Implementation of FRI model in *ChemSep***
4. **Applications of the FRI Model**
5. **Concluding Remarks**

Efficiency Concepts



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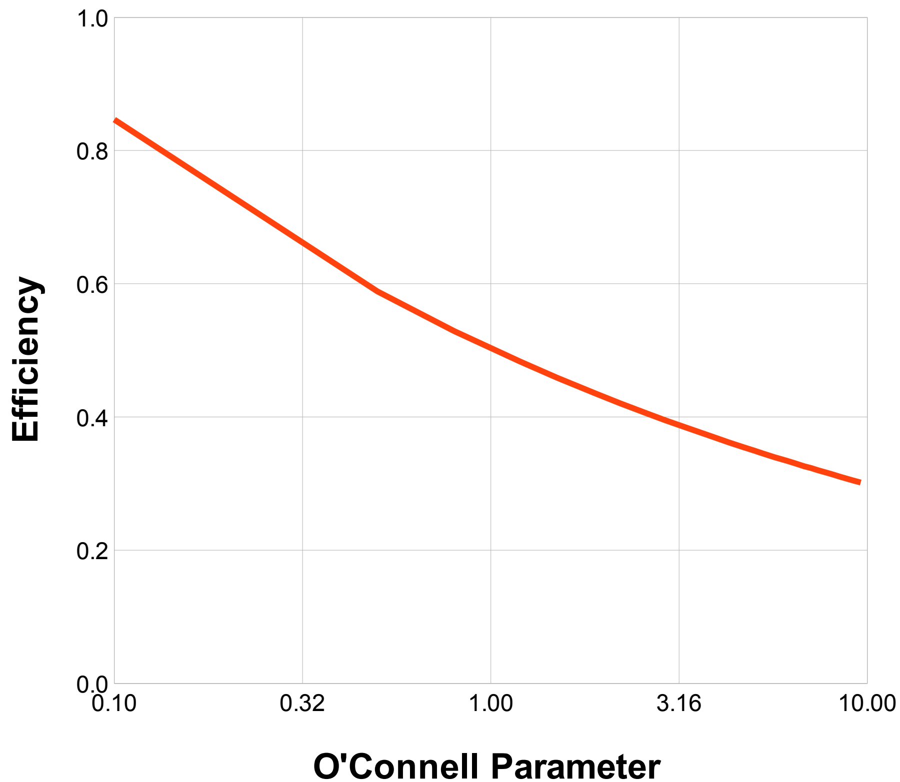
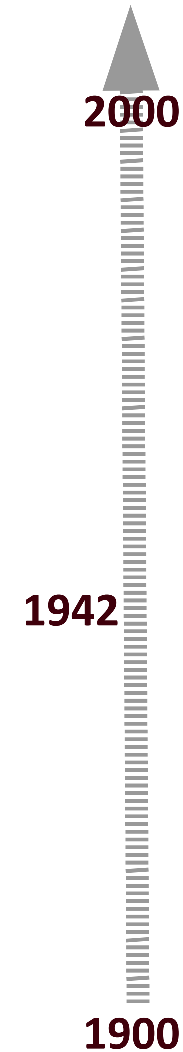
The concept of the theoretical plate does not offer a satisfactory basis for calculation of rectifying columns when the mixture … contains more than two components.

E.V. Murphree (1925)

$$E_{MV} = \frac{\text{Actual composition change}}{\text{Equilibrium composition change}} = \frac{\Delta y_{i,L}}{\Delta y_i^*}$$

O'Connell Correlation





$$E_O = 50.3(\alpha \mu)^{-0.226}$$

α **relative volatility between keys**

μ **liquid viscosity in cP**

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Bubble Geometry Efficiency Models: Milestones

FRI

S.R. Syeda et al.

2000 — J.A. Garcia and J.R. Fair

M. Prado and J.R. Fair

M.J. Lockett

M.J. Lockett and T. Plaka

H. Hofer

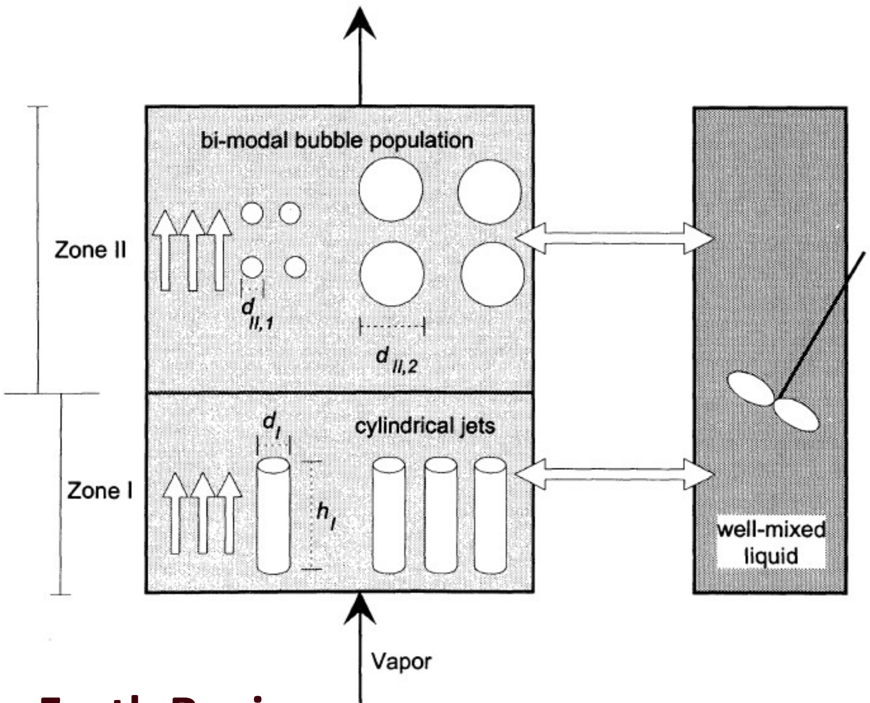
E. Kaltenbacher

1980

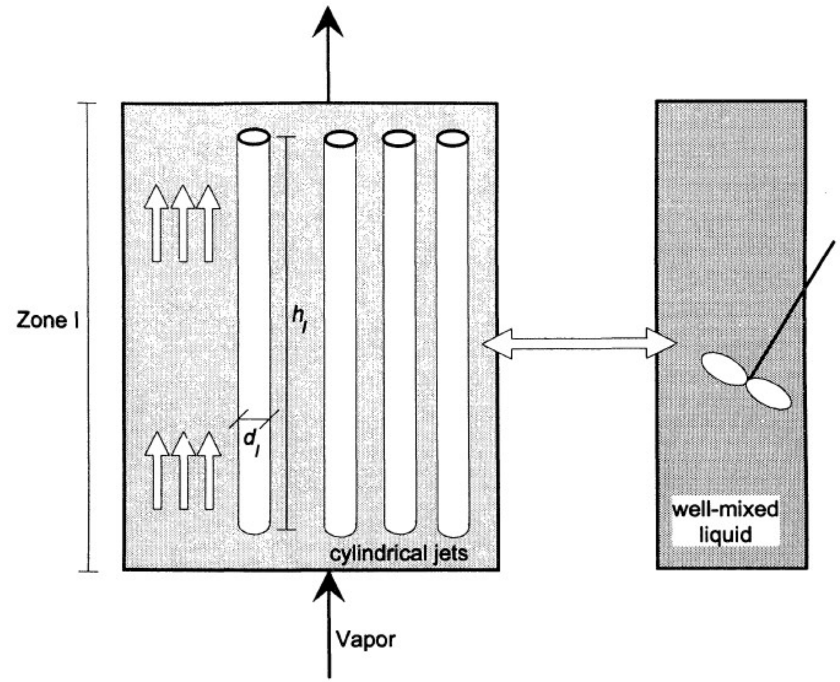
1940 — R. L. Geddes

1930 — J.S. Carey (Sc.D. Thesis, 1930)

Bubble Geometry Efficiency Models: Physics



Froth Regime



Spray Regime

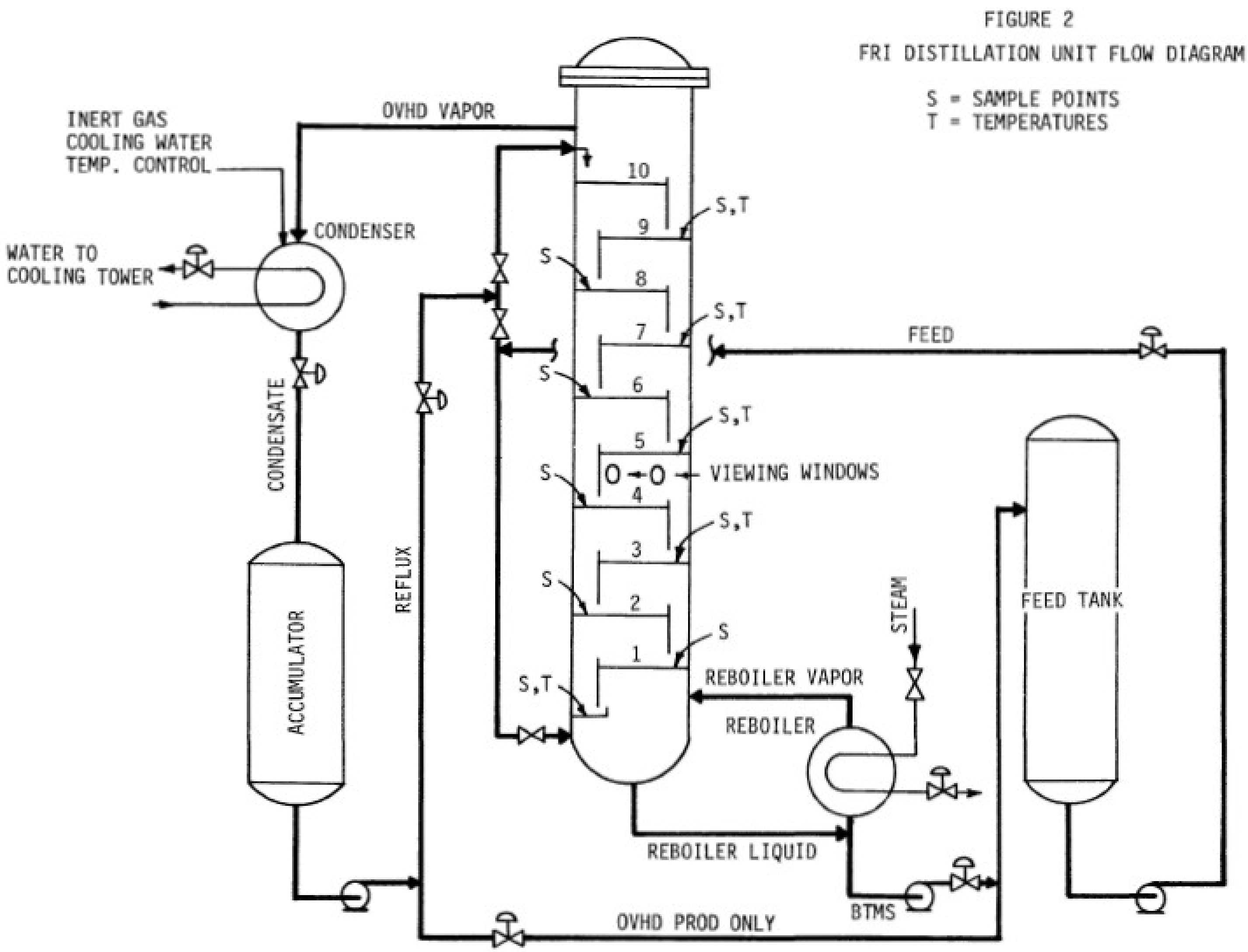
Zone I	Zone II
Height	Small bubble diameter
Diameter	Large bubble diameter
	Small bubble rise velocity
	Large bubble rise velocity
	Fraction small bubbles

Case Studies

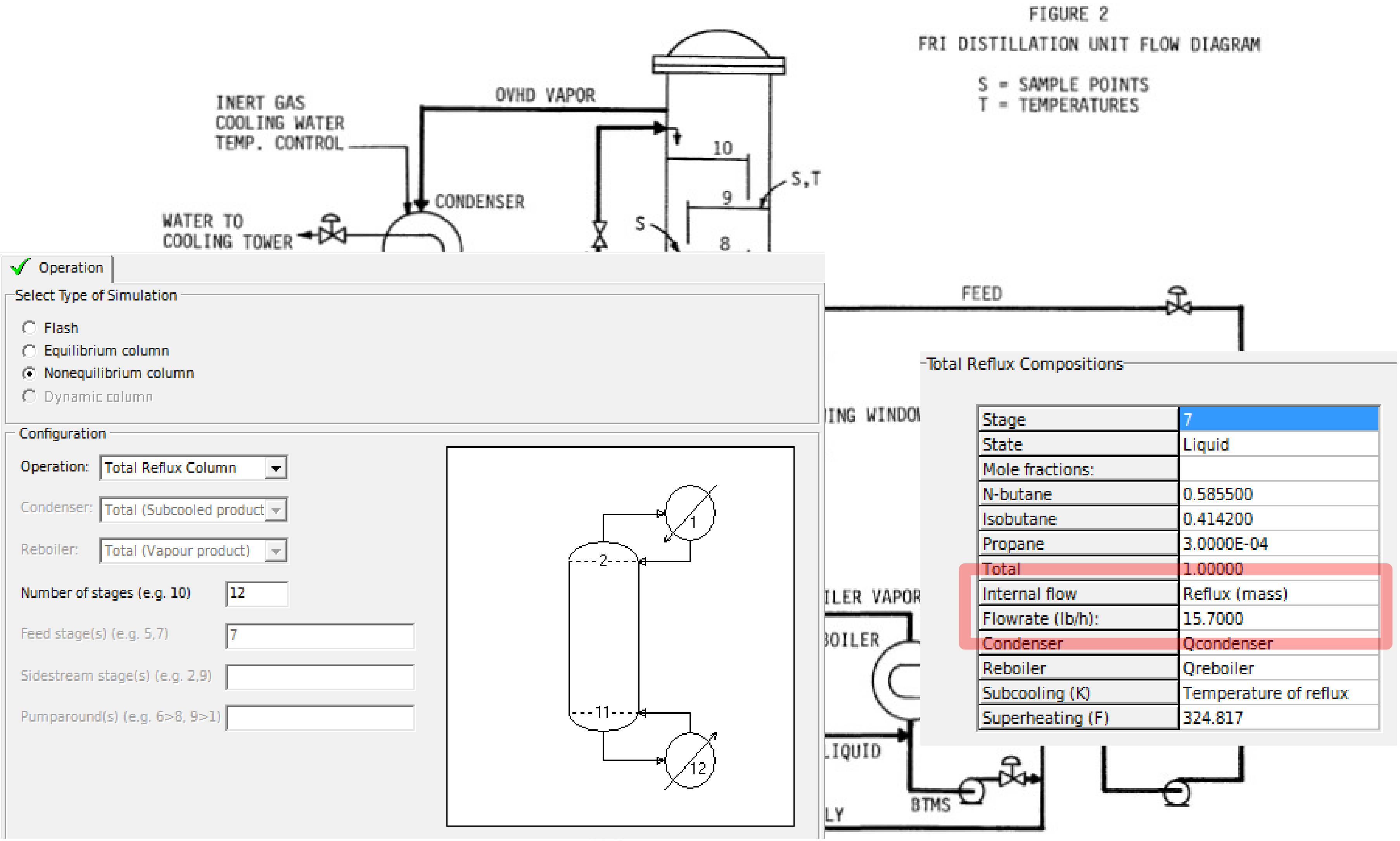
1. FRI Test System I: nC4 – iC4 – C3 @ 165 psia
2. FRI Test System II: o-Xylene – p-Xylene @ 20 mm Hg
3. Industrial Case Study I: C4 splitter
4. Industrial Case Study II: Dehexanizer
5. Design Case Study: BTX column

T. Yanagi, *FRI Topical Report* 041, 1967,
Glitsch V-0 Ballast Tray,
Available from Oklahoma State University
Special Collections and University Archives.

The FRI Column

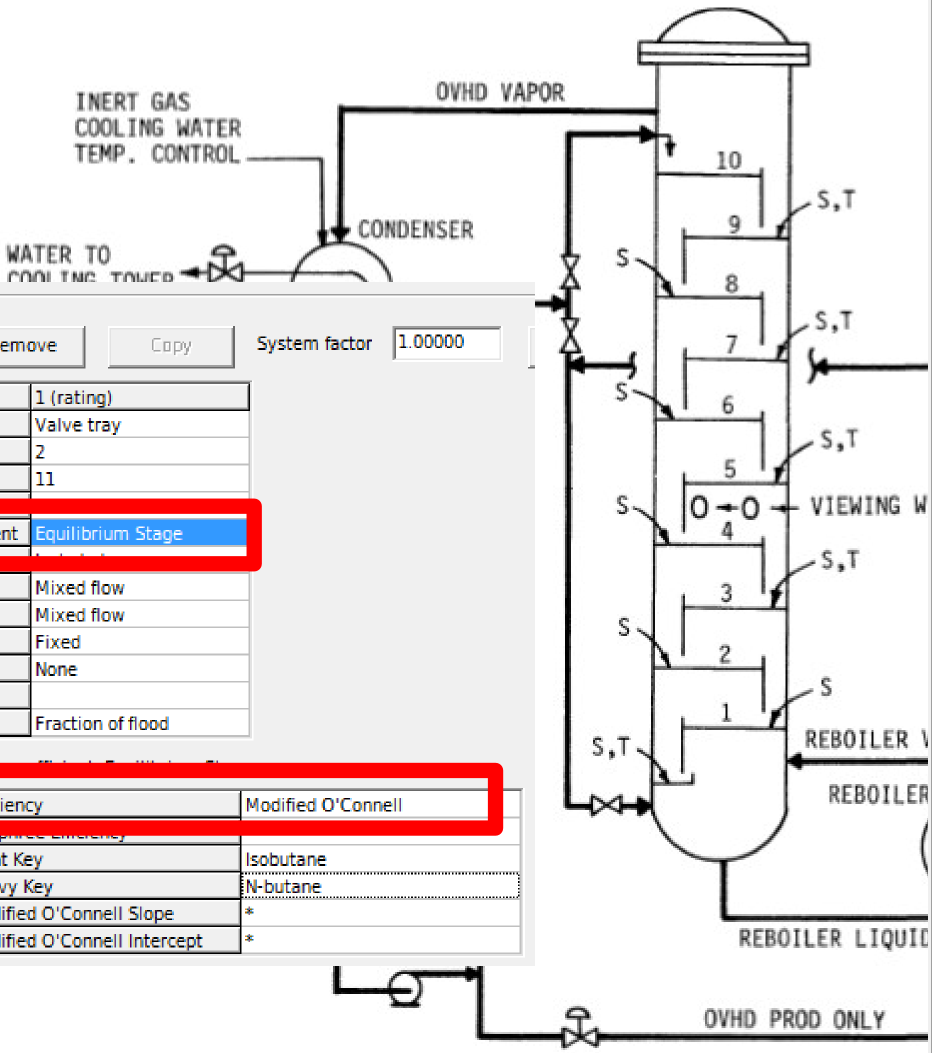


Modeling the FRI Column in ChemSep



Stage	7
State	Liquid
Mole fractions:	
N-butane	0.585500
Isobutane	0.414200
Propane	3.0000E-04
Total	1.00000
Internal flow	Reflux (mass)
Flowrate (lb/h):	15.7000
Condenser	Qcondenser
Reboiler	Qreboiler
Subcooling (K)	Temperature of reflux
Superheating (F)	324.817

Modeling the FRI Column in ChemSep



Internals Design

Insert | Remove | Copy | System factor 1.00000

Section	1 (rating)
Column internals	Valve tray
First stage	2
Last stage	11
Mass transfer coefficient	Equilibrium Stage
Vapour flow model	Mixed flow
Liquid flow model	Mixed flow
Pressure drop	Fixed
Entrainment	None
Holdup	
Design method	Fraction of flood

Section 1 Mass t

Load | Save | Reset

Efficiency	Modified O'Connell
Light Key	Isobutane
Heavy Key	N-butane
Modified O'Connell Slope	*
Modified O'Connell Intercept	*

Internals Design

Insert | Remove | Copy | System factor 1.00000

Section	1 (rating)
Column internals	Valve tray
First stage	2
Last stage	11
Section height (m)	6.09600
Mass transfer coefficient	Equilibrium Stage
Liquid phase resistance	Included
Vapour flow model	Mixed flow
Liquid flow model	Mixed flow
Pressure drop	Fixed
Entrainment	None
Holdup	
Design method	Fraction of flood

Section 1 Column internals: Valve tray

Load | Save | Reset

Column diameter (m)	1.21920
Tray spacing (mm)	609.600
Number of flow passes	1.00000
Liquid flow path length (mm)	787.400
Active area (m2)	0.888153
Total hole area (m2)	0.135220
Downcomer area (m2)	*
Hole diameter (mm)	12.7000
Hole pitch (mm)	*
Weir length (m)	0.939800
Weir height (mm)	63.5000
Weir type	Segmental
Notch depth/Weir diameter (mm	*
Serration angle (rad)	*
Downcomer clearance (mm)	*
Deck thickness (mm)	1.98000
Downcomer sloping	*
Downcomer length	*
Closed Loss K	*
Open Loss K	*
Eddy Loss C	*
Ratio Valve Legs	*
Valve Density	7680.00
Valve Thickness	*
Fraction Heavy Valves	0.000000
Heavy Valve Thickness	*

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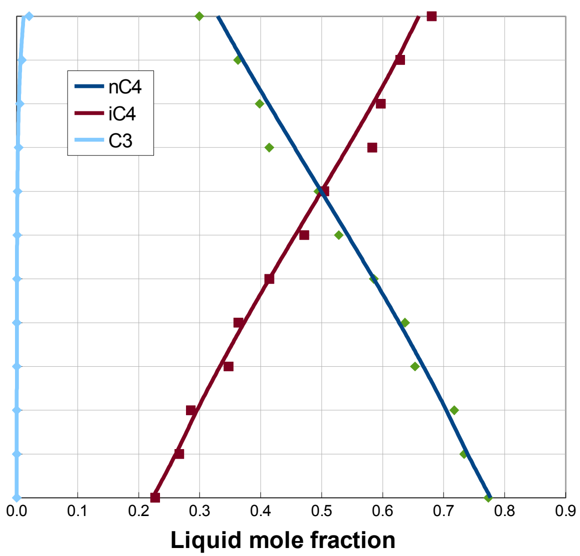
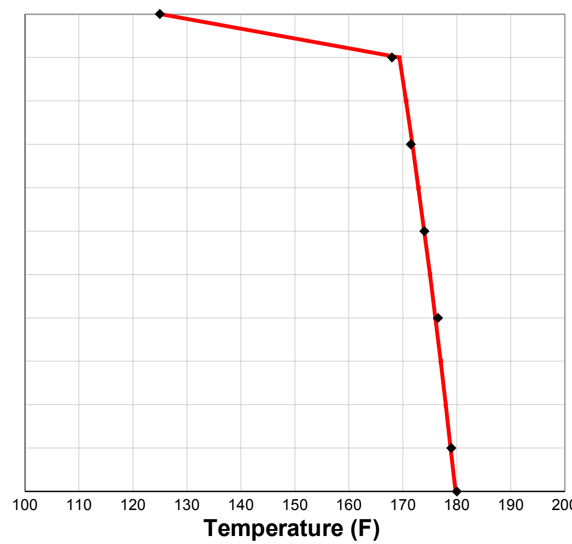
T. Yanagi, *FRI Topical Report* 041, 1967,
Glitsch V-0 Ballast Tray,
Available from Oklahoma State University
Special Collections and University Archives.

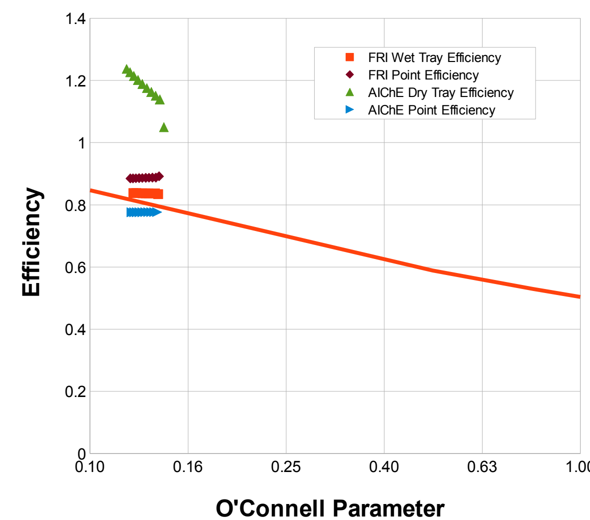
FRI Test 9276: n-C4 – iC4 – C3 @ 165 psia

Tray Type	Glitsch Ballast Tray
Valves	114 V-0 units
Tray spacing	24 in
Weir length	37 in
Weir height	2.5 in
Downcomer Area	1.5 ft^2

	TR 041	Simulation
Condenser Duty (MM Btu/h)	2.56	2.33
Reboiler Duty (MM Btu/h)	2.30	2.33
Tray 4 liquid density (lb/ft^3)	30.7	30.5
Tray 4 vapor density (lb/ft^3)	1.78	1.81
Tray Efficiency (%)	91.9	83.7







Composition and temperature profiles with FRI tray efficiency model.

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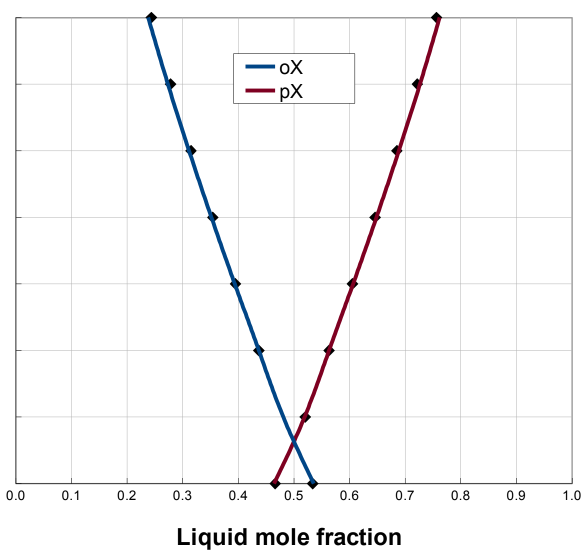
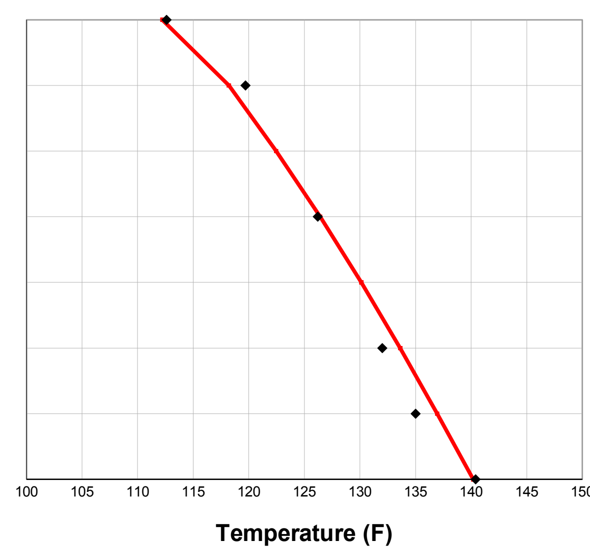
M. Sakata, *FRI Topical Report* 044, 1968,
Tests of the Koch Type "T" Flexitray in High Vacuum Fractionation,
Available from Oklahoma State University Special Collections and University Archives.

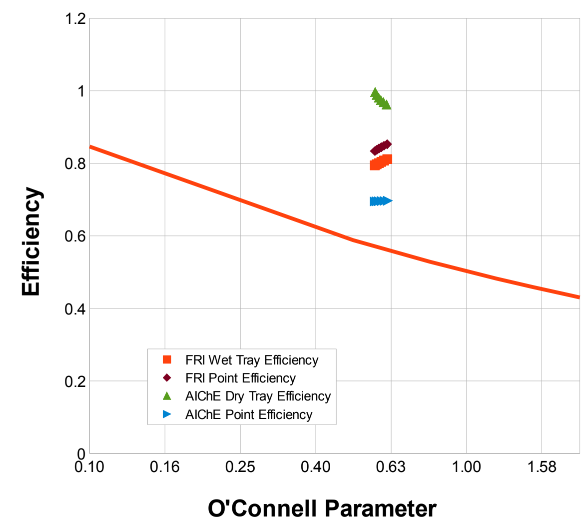
FRI Test 9346: o-Xylene – p-Xylene @ 20 mmHg

Tray Type	Koch Flexitray Type T
Valves	167 double weight
Tray spacing	24 in
Weir length	30 in
Weir height	0.75 in
Downcomer Area	0.53 ft^2

	TR 044	Simulation
Condenser Duty (MM Btu/h)	0.976	0.941
Reboiler Duty (MM Btu/h)	0.934	0.941
Tray 2 liquid density (lb/ft^3)	52.4	52.3
Tray 2 vapor density (lb/ft^3)	0.0122	0.0139
Tray Efficiency (%)	77.0	79.4-81.5







Composition and temperature profiles with FRI tray efficiency model.

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ChemSep *Modeling Separation Processes*

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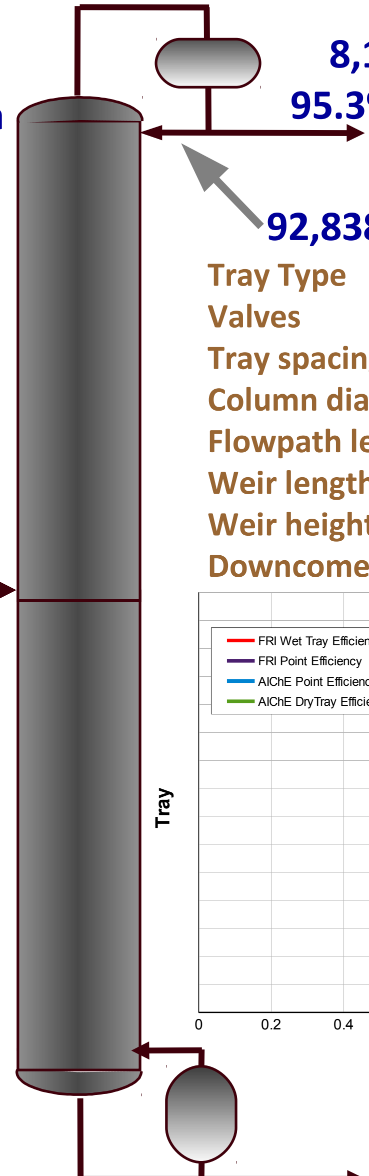
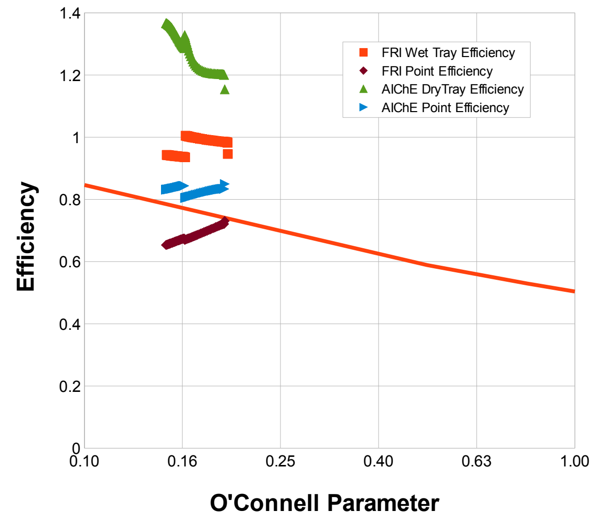
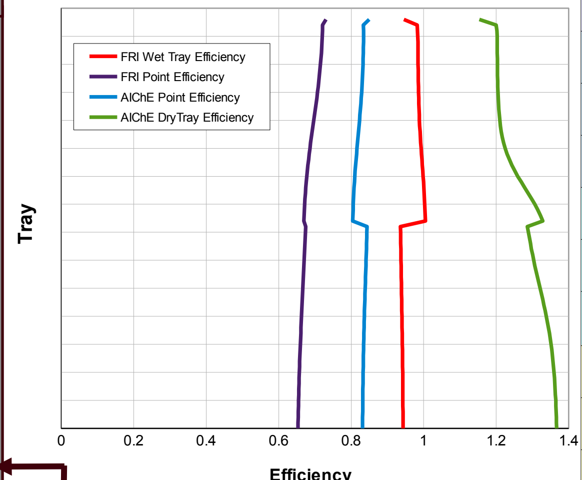
K.T. Klemola and J. Ilme: Distillation Efficiencies of an Industrial-Scale *i*-Butane/*n*-Butane Fractionator *Ind. Eng. Chem. Res.* 1996, *35*, 4579-4586.

C4 Splitter



Tray Type	74 Two-pass Ballast trays
Valves	772 V-1
Tray spacing	600 mm
Column diameter	2.900 m
Flowpath length	0.967 m per pass
Weir lengths	1.859 m, 2.885 m
Weir height	51 mm
Downcomer Area	2 x 0.86 m^2





Type	Value(%)	NTU Model	Thermo	Source
Overall	111		SRK	Ilme Ph.D. thesis
Overall	119		UNIFAC	Klemola + Ilme
Overall	114		PR	Taylor and Kooijman
Point	75-82	AIChE	UNIFAC	Klemola + Ilme
Point	81-85	AIChE	SRK	This work
Point	66-75	FRI	SRK	This work
Tray	115-120	AIChE	UNIFAC	Klemola + Ilme
Dry Tray	115-137	AIChE	SRK	This work
Wet Tray	93-101	FRI	SRK	This work

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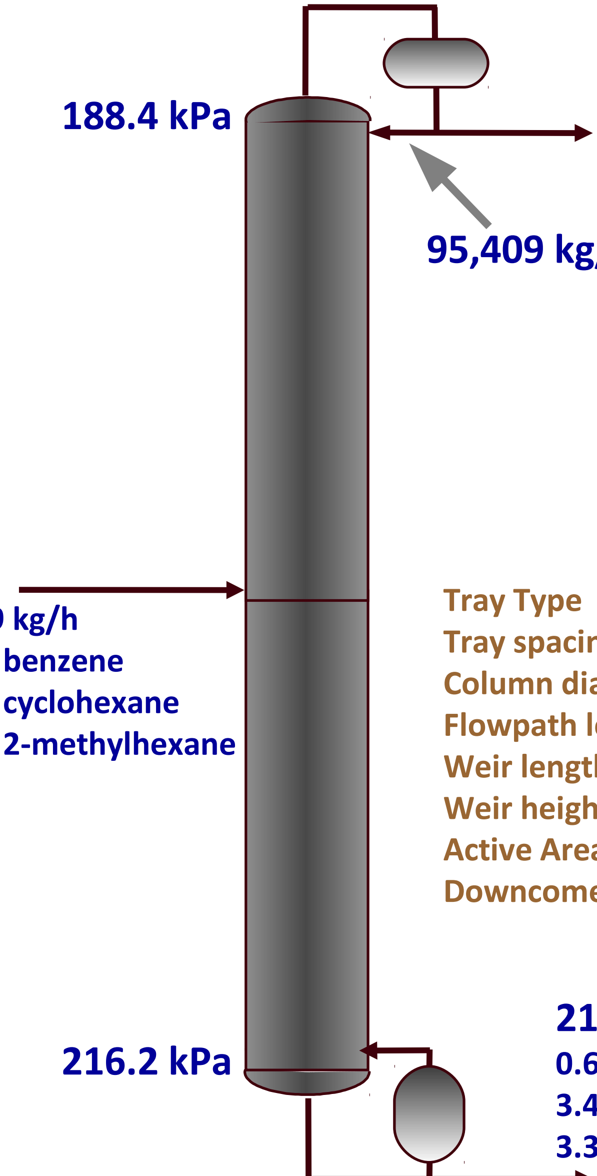
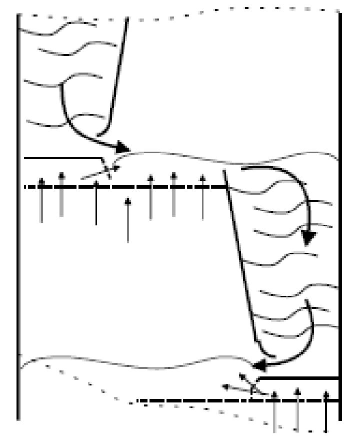
K. Jakobsson, J. Aittamaa, K. Keskinen, J. Ilme, Plate Efficiencies of Industrial Scale Dehexaniser, International Conference on Distillation & Absorption, Kongresshaus, Baden-Baden, Germany 30 September — 2 October 2002

Dehexaniser



Type	Value(%)	NTU Model	Thermo	Source
Point	75-85	Chan + Fair	SRK	Jakobsson et al.
Point	75-97	AIChE	SRK	This work
Tray	85-110	Chan + Fair	SRK	Jakobsson et al.
Tray	80-110	FRI	SRK	This work

Tray Type	40 Nye Type Valve Trays
Tray spacing	600 mm
Column diameter	3.672 m
Flowpath length	1.178 m per pass
Weir lengths	6.318 m
Weir height	57 mm
Active Area	8.58 m^2
Downcomer Area	1.142 m^2



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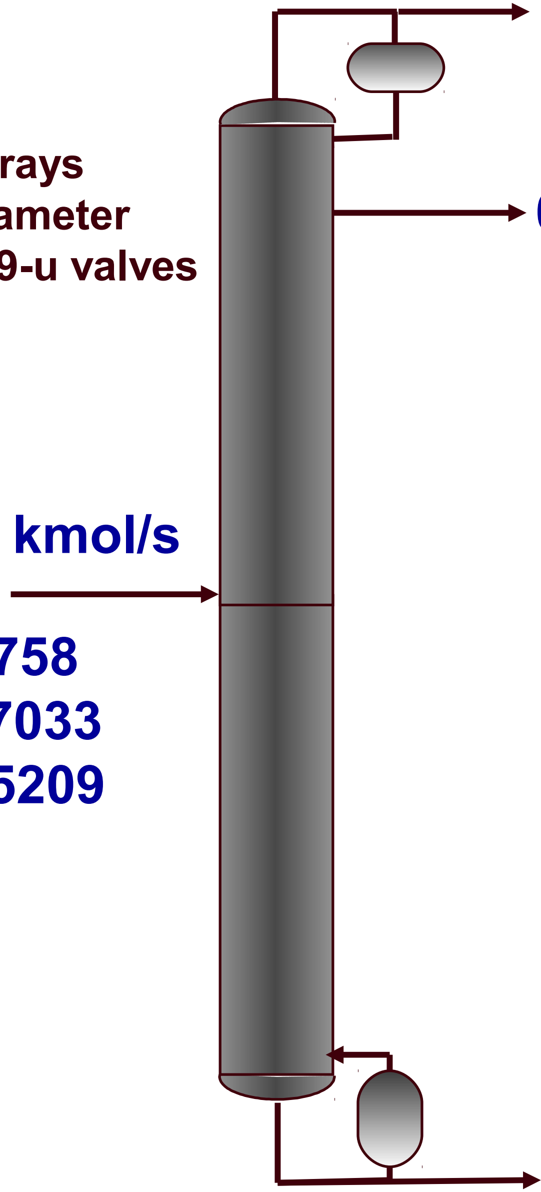
Biddulph and Ashton, Chem. Eng. J., 1977

Design Case Study: BTX Column

54 valve trays
2.43 m diameter
Koch Kx-9-u valves



0.0285124 kmol/s

Data	Simulation
B: 0.999958	B: 0.999911
T: 0.0000419	T: 0.0000886
X: ~0	X: ~0

.0766893 kmol/s

B: 0.317758
T: 0.5727033
X: 0.0555209

Data — Simulation

Data	Simulation
B: ~0	B: 0.0000283
T: 0.9116191	T: 0.911592
X: 0.0883806	X: 0.0883797

0.0481769 kmol/s

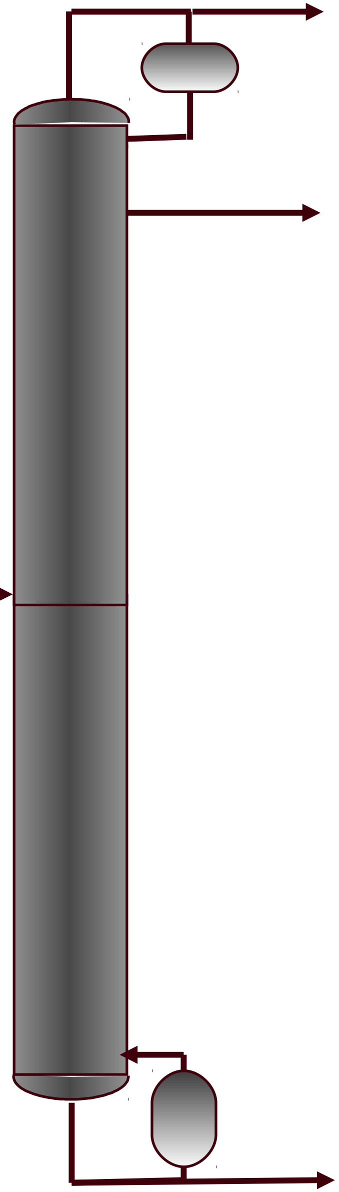
Biddulph and Ashton, Chem. Eng. J., 1977

Design Case Study: BTX Column

54 valve trays
2.43 m diameter
Koch Kx-9-u valves

.0766893 kmol/s

B: 0.317758
T: 0.5727033
X: 0.0555209



Select table: Internals design | XLS | Edit | Copy | Font

Tray design produced by ChemSep.
FRI model used only for efficiency, not for tray sizing.

```
Column design:

 Number of sections                              1
 Default system factor ( )                0.900000

 Section                                         1
  Column internals                           Valve
  First stage                                    2
  Last stage                                    55
  Flood limit @stage                    65% jf @26
  Section height (m)
  Column diameter (m)                            2
  Tray spacing (mm)                            610
  Number of flow passes                          2
  Liquid flow path length (mm)             748.429
  Active area (m2)                         2.57507
  Total hole area (m2)                    0.630425
  Downcomer area (m2)                     0.283258
  Hole diameter (mm)                          50.8
  Hole pitch (mm)                          97.8704
  Weir length (m)                          2.30029
  Weir height (mm)                           54.08
  Weir type                              Segmental
  Notch depth/Weir diameter (mm                  *
  Serration angle (rad)                          *
  Downcomer clearance (mm)                   41.38
  Deck thickness (mm)                         2.54
  Downcomer sloping                              0
  Downcomer length                               1
  Closed Loss K                             0.8413
  Open Loss K                               0.1225
  Eddy Loss C                                  1.3
  Ratio Valve Legs                            1.29
  Valve Density                               7849
  Valve Thickness                            0.003
  Fraction Heavy Valves                          0
  Heavy Valve Thickness                          0

 jf=jet flood, dv=downcomer velocity, bu=Backup, ck=Downcomer choking
 sl=system limit, wl=weir loading, rt=residence time
 wp=weeping/insufficient wetting, dp=dumping/unsealing, sb=stability
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Concluding Remarks and Proposed Next Steps

1. Bubble GEMs are comprehensive models of tray efficiency that separate the contributions to mass transfer from jetting and different bubble populations. This separation permits the systematic exploration of mass transfer in different flow regimes.

2. FRI valve tray efficiency model is *complete* (in that the model is self-contained).

3. FRI model was implemented as an "added model" for *ChemSep*.

4. Tests of the *ChemSep* implementation show very good match with FRI distillation data at total reflux.

5. Tentative: Simulations of some commercial scale processes suggest that the FRI model is not able to match the observed overall efficiencies so well.

6. FRI model can be used at the design stage.

7. FRI model should be extended to sieve trays.

8. Column profile data for operations *not* at total reflux would be useful.

Bubble Geometry Efficiency Models: References

Geddes, R.L. (Local Efficiencies of Bubble Plate Fractionators, *Trans. AIChE*, XLII, 79-105, 1946)

Kaltenbacher, E., On the Effect of the Bubble Size Distribution and the Gas Phase Diffusion on the Selectivity of Sieve Trays, *Chem. Eng. Fundam.,* 1, 47-68 (1982)

Hofer, H., Influence of Gas-phase Dispersion on Plate Column Efficiency, *Ger. Chem. Eng.*, 6, 113-118 (1983)

Lockett, M. J. and Plaka, T., Effect of Non-Uniform Bubbles in the Froth on the Correlation and Prediction of Point Efficiencies, *Chem. Eng. Res. Des.*, 61, 119-124 (1983)

Lockett, M. J., *Distillation Tray Fundamentals*, Cambridge University Press, Cambridge, England (1986)

Krishna, R., Model for Prediction of Point Efficiencies for Multicomponent Distillation, *Chem. Eng.Res. Des.,* 63, 312-322 (1985)

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Garcia, J. A., and Fair, J. R. A Fundamental Model for the Prediction of Distillation Sieve Tray Efficiency. 2. Model Development and Validation. *Ind. Eng. Chem. Res.*, 39, 1818 (2000)

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Vennavelli, A.N., Whitely, J.R. & Resetarits, M.R. New Fraction Jetting Model for Distillation Sieve Tray Efficiency Prediction, *Ind. Eng. Chem. Res.*, 51, 11458-11462 (2012)