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

2013 AIChE Spring Meeting – San Antonio

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Attilio J. Praderio - ConocoPhillips - LNG Technology
Special thanks to FRI

Mike Resetarits
Anand Vennavelli
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

Equipment design
Mass transfer
Fluid flow model
Computational method
Phase equilibrium
Summation equations
Energy balances
Mass balances

Geometric (Baur)
Bubble GEMs
Generalized Hausen (Standard)
AIChe method
Hausen
O'Connell
Vaporization (McAdams)?
Lewis Cases
Murphree
Overall Efficiency (Lewis)

“Rigorous” Model (Equilibrium stage)
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)

\[
E_{MV} = \frac{\text{Actual composition change}}{\text{Equilibrium composition change}} = \frac{\Delta y_{i,L}}{\Delta y_i^*}
\]
\[ E_O = 50.3 (\alpha \mu)^{-0.226} \]

\[ \alpha \mu \]

relative volatility between keys
liquid viscosity in cP

O'Connell Correlation

O'Connell Parameter

Efficiency

1900
1942
2000
Bubble Geometry Efficiency Models: Milestones

- **1940**: R. L. Geddes
- **1980**: M. Prado and J.R. Fair
- **1990**: M.J. Lockett
- **2000**: J.A. Garcia and J.R. Fair
Froth Regime

<table>
<thead>
<tr>
<th>Zone I</th>
<th>Zone II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>Small bubble diameter</td>
</tr>
<tr>
<td>Diameter</td>
<td>Large bubble diameter</td>
</tr>
<tr>
<td>Small bubble rise velocity</td>
<td>Large bubble rise velocity</td>
</tr>
<tr>
<td>Fraction small bubbles</td>
<td></td>
</tr>
</tbody>
</table>

Spray Regime

Bubble Geometry Efficiency Models: Physics
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
The FRI Column

T. Yanagi, FRI Topical Report 041, 1967, Glitsch V-0 Ballast Tray, Available from Oklahoma State University Special Collections and University Archives.
Modeling the FRI Column in ChemSep
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 ft²

Condenser Duty (MM Btu/h) | TR 041 | Simulation
-------------------------|--------|--------
2.56                     | 2.33   |
Reboiler Duty (MM Btu/h)  | 2.30   | 2.33   |
Tray 4 liquid density (lb/ft³) | 30.7   | 30.5   |
Tray 4 vapor density (lb/ft³) | 1.78   | 1.81   |
Tray Efficiency (%)       | 91.9   | 83.7   |

Composition and temperature profiles with FRI tray efficiency model.
FRI Test 9346: o-Xylene – p-Xylene @ 20 mmHg

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.

<table>
<thead>
<tr>
<th>Tray Type</th>
<th>Koch Flexitray Type T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valves</td>
<td>167 double weight</td>
</tr>
<tr>
<td>Tray spacing</td>
<td>24 in</td>
</tr>
<tr>
<td>Weir length</td>
<td>30 in</td>
</tr>
<tr>
<td>Weir height</td>
<td>0.75 in</td>
</tr>
<tr>
<td>Downcomer Area</td>
<td>0.53 ft²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>TR 044</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser Duty (MM Btu/h)</td>
<td>0.976</td>
<td>0.941</td>
</tr>
<tr>
<td>Reboiler Duty (MM Btu/h)</td>
<td>0.934</td>
<td>0.941</td>
</tr>
<tr>
<td>Tray 2 liquid density (lb/ft³)</td>
<td>52.4</td>
<td>52.3</td>
</tr>
<tr>
<td>Tray 2 vapor density (lb/ft³)</td>
<td>0.0122</td>
<td>0.0139</td>
</tr>
<tr>
<td>Tray Efficiency (%)</td>
<td>77.0</td>
<td>79.4-81.5</td>
</tr>
</tbody>
</table>

Composition and temperature profiles with FRI tray efficiency model.
K.T. Klemola and J. Ilme: Distillation Efficiencies of an Industrial-Scale i-Butane/n-Butane Fractionator

![Diagram of C4 Splitter]

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

**Tray Details**
- **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 m²

**Gas Flow**
- **8,115 kg/h**: 95.3% i-butane
- **92,838 kg/h**: 26,234 kg/h
  - 29.4% i-butane
  - 67.7% n-butane
  - **18,119 kg/h**: 98.1% n-butane

**Pressure**: 658.6 kPa
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

283,839 kg/h
1.221% benzene
3.527% cyclohexane
2.575% 2-methylhexane

69,768 kg/h
2.961% benzene
3.821% cyclohexane
0.255% 2-methylhexane

95,409 kg/h

216.2 kPa

214,071 kg/h
0.653% benzene
3.432% cyclohexane
3.331% 2-methylhexane

<table>
<thead>
<tr>
<th>Type</th>
<th>Value(%)</th>
<th>NTU Model</th>
<th>Thermo</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point</td>
<td>75-85</td>
<td>Chan + Fair</td>
<td>SRK</td>
<td>Jakobsson et al.</td>
</tr>
<tr>
<td>Point</td>
<td>75-97</td>
<td>AIChE</td>
<td>SRK</td>
<td>This work</td>
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<td>80-110</td>
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<td>This work</td>
</tr>
</tbody>
</table>
Design Case Study: BTX Column

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

**Data**

- B: 0.317758
- T: 0.5727033
- X: 0.0555209

- 0.0285124 kmol/s
- B: 0.999958
- T: 0.0000419
- X: ~0

- 0.0481769 kmol/s
- B: 0.999911
- T: 0.0000886
- X: ~0

**Simulation**

- B: 0.0000283
- T: 0.9116191
- X: 0.0883806

- 0.0766893 kmol/s

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


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

Column design:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sections</td>
<td>1</td>
</tr>
<tr>
<td>Default system factor ( )</td>
<td>0.900000</td>
</tr>
<tr>
<td>Section</td>
<td></td>
</tr>
<tr>
<td>Column internals</td>
<td>Valve</td>
</tr>
<tr>
<td>First stage</td>
<td></td>
</tr>
<tr>
<td>Last stage</td>
<td></td>
</tr>
<tr>
<td>Flood limit @ stage</td>
<td>65% jet @26</td>
</tr>
<tr>
<td>Section height (m)</td>
<td></td>
</tr>
<tr>
<td>Column diameter (m)</td>
<td></td>
</tr>
<tr>
<td>Tray spacing (mm)</td>
<td></td>
</tr>
<tr>
<td>Number of flow passes</td>
<td>2</td>
</tr>
<tr>
<td>Liquid flow path length (mm)</td>
<td></td>
</tr>
<tr>
<td>Active area (m²)</td>
<td></td>
</tr>
<tr>
<td>Total hole area (m²)</td>
<td></td>
</tr>
<tr>
<td>Downcomer area (m²)</td>
<td></td>
</tr>
<tr>
<td>Hole diameter (mm)</td>
<td></td>
</tr>
<tr>
<td>Hole pitch (mm)</td>
<td></td>
</tr>
<tr>
<td>Weir length (m)</td>
<td></td>
</tr>
<tr>
<td>Weir height (mm)</td>
<td></td>
</tr>
<tr>
<td>Weir type</td>
<td>Segmental</td>
</tr>
<tr>
<td>Notch depth/Weir diameter (mm)</td>
<td></td>
</tr>
<tr>
<td>Serration angle (rad)</td>
<td></td>
</tr>
<tr>
<td>Downcomer clearance (mm)</td>
<td></td>
</tr>
<tr>
<td>Deck thickness (mm)</td>
<td></td>
</tr>
<tr>
<td>Downcomer sloping</td>
<td></td>
</tr>
<tr>
<td>Downcomer length</td>
<td></td>
</tr>
<tr>
<td>Closed Loss K</td>
<td>0.8413</td>
</tr>
<tr>
<td>Open Loss K</td>
<td>0.1225</td>
</tr>
<tr>
<td>Eddy Loss C</td>
<td>1.3</td>
</tr>
<tr>
<td>Ratio Valve Legs</td>
<td>1.29</td>
</tr>
<tr>
<td>Valve Density</td>
<td>7849</td>
</tr>
<tr>
<td>Valve Thickness</td>
<td>0.003</td>
</tr>
<tr>
<td>Heavy Valve Thickness</td>
<td>0</td>
</tr>
<tr>
<td>Heavy Valve Thickness</td>
<td>0</td>
</tr>
</tbody>
</table>

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
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)


