A Rate-Based Equation-Oriented Parallel Column Model: Application to Dividing Wall Columns

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Dividing Wall Columns: What Was Said

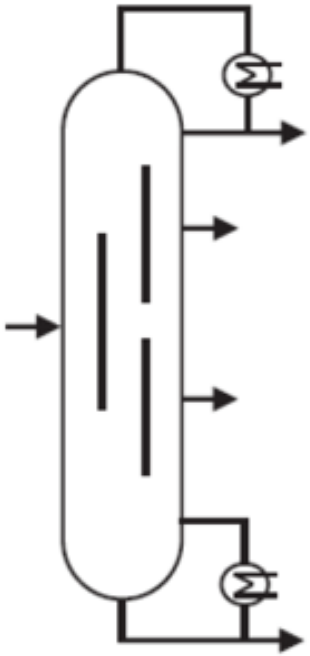
Dejanović et al. (2010) wrote:

*Carrying out DWC performance simulations **requires great experience** and these are more or less computationally very demanding. … well established commercial software packages still do not contain a DWC as a standard model.*

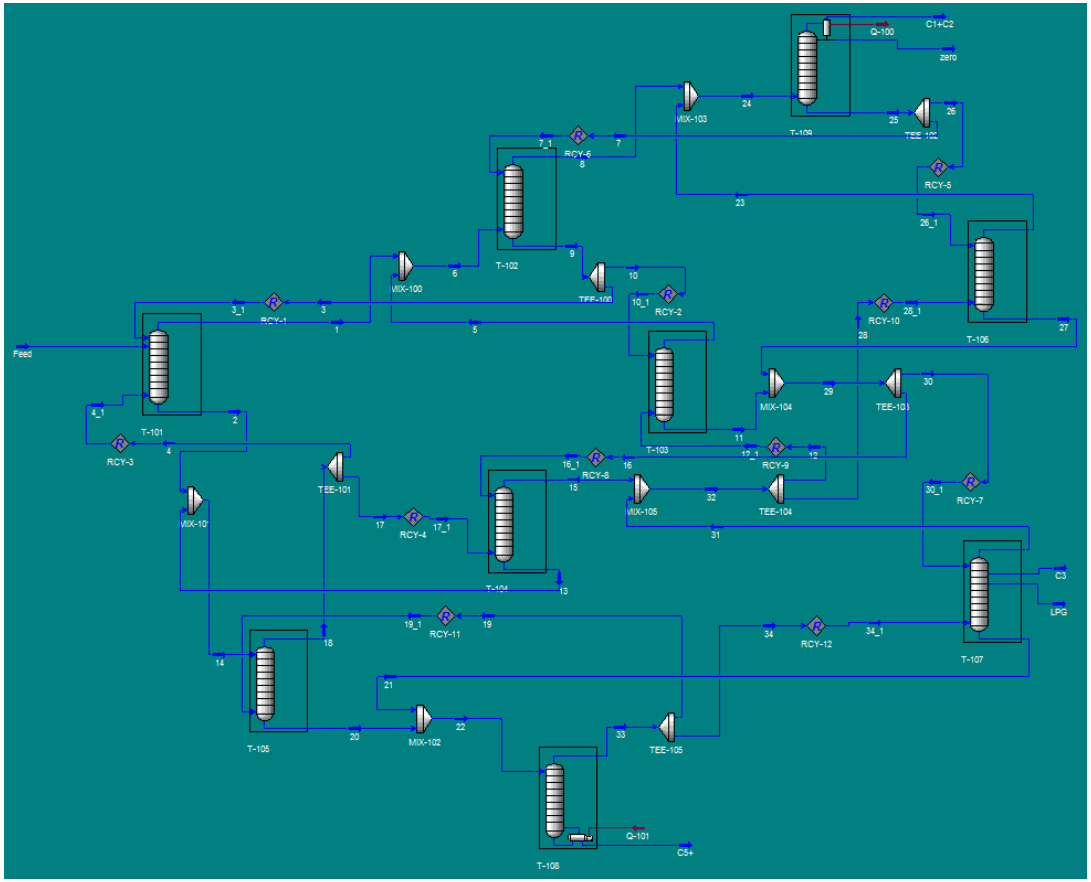
Engineers have, therefore, developed alternative approaches to model DWCs…

Dividing Wall Columns: What Was Done

Dividing Wall Column



Simulated with a multi-column model, this example in UNISIM Design



Ashrafian, R. (2014). *Using Dividing Wall Columns (DWC) in LNG Production: deviding wall column, double dividing wall column, prefractionator arrangement, Petlyuk column, NGL recovery, distillation* (Master's thesis, Institutt for energi-og prosessteknikk).

Dividing Wall Columns: What Was Said

Dejanović et al. (2010) wrote:

*Carrying out DWC performance simulations **requires great experience** and these are more or less computationally very demanding. … well established commercial software packages still do not contain a DWC as a standard model. **This however will occur sooner or later, most probably as a simultaneous, equation based model.***

Kaibel (2014) wrote:

*Due to the potential variability of complex internal configurations, there is no dedicated software package for this purpose. … The convergence behavior of programs with sequential operation is **sometimes problematic**. **Equation-based programs normally show better convergence characteristics**.*

But no evidence in support of this assertion had been presented.

Dividing Wall Columns: What Was Said

Clarkson UNIVERSITY defy convention

Dejanović et al. (2010) wrote:

*Carrying out DWC performance simulations **requires great experience** and these are more or less computationally very demanding. … well established commercial software packages still do not contain a DWC as a standard model. **This however will occur sooner or later, most probably as a simultaneous, equation based model.***

This, now, has been done.

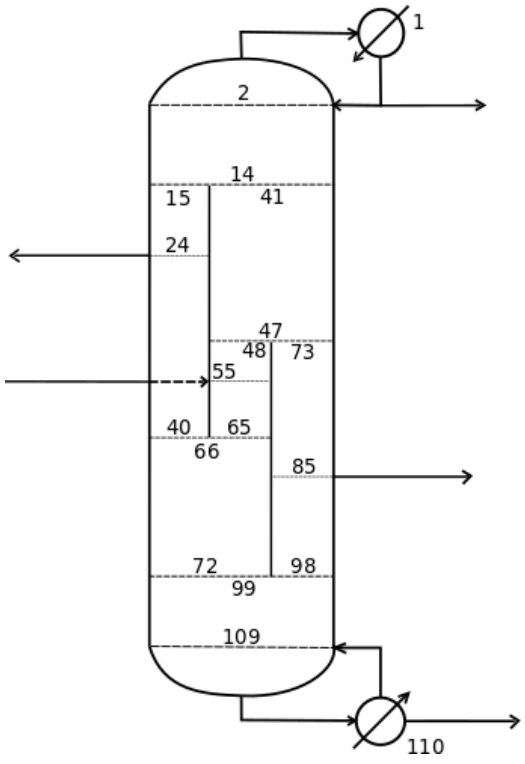
Kaibel (2014) wrote:

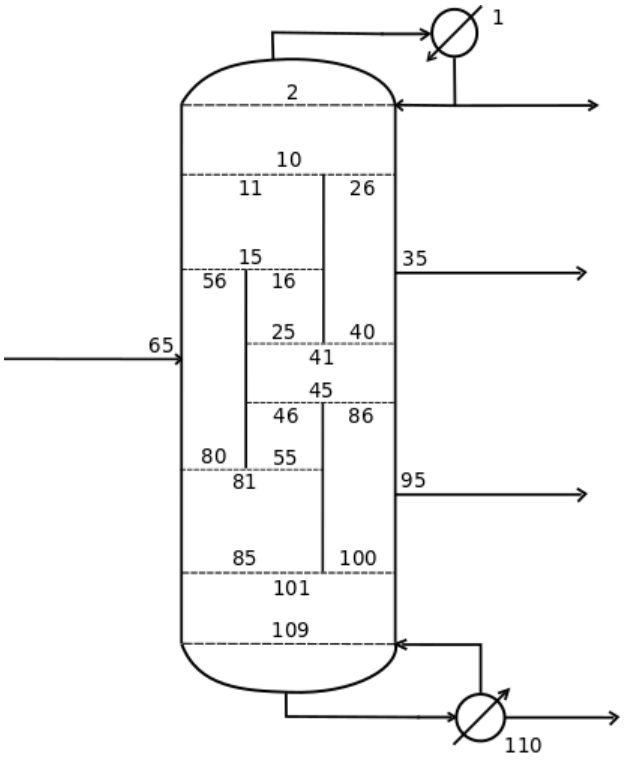
*Due to the potential variability of complex internal configurations, there is no dedicated software package for this purpose. … The convergence behavior of programs with sequential operation is **sometimes problematic**. **Equation-based programs normally show better convergence characteristics**.*

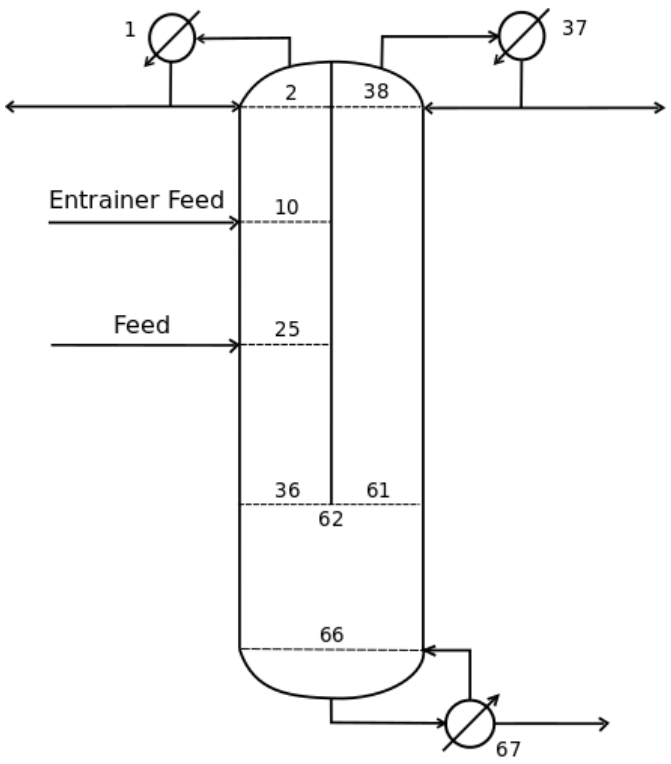
We now have abundant evidence to show that this, also, is true!

Dividing Wall Columns: What We Did

- Equation-oriented parallel column model (PCM)
  - Simulates dividing wall columns (DWCs) of arbitrary configuration

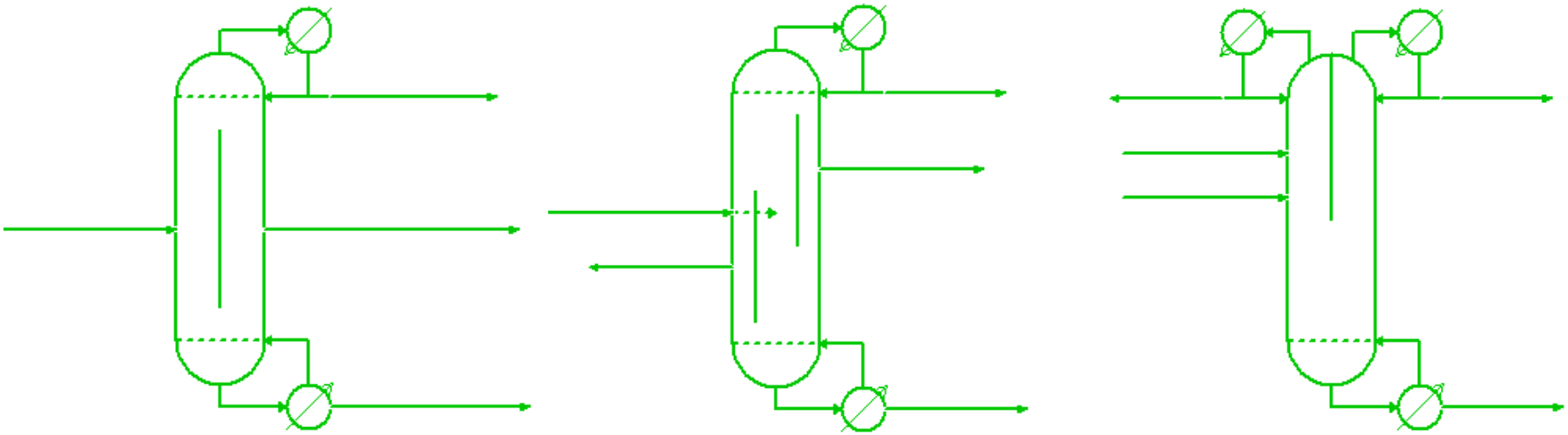






ChemSep Parallel Column Model: What's New

- Flowsheet simulation with CAPE-OPEN compliant PCM
- Rate-based Parallel Column Model
- Maldistribution model

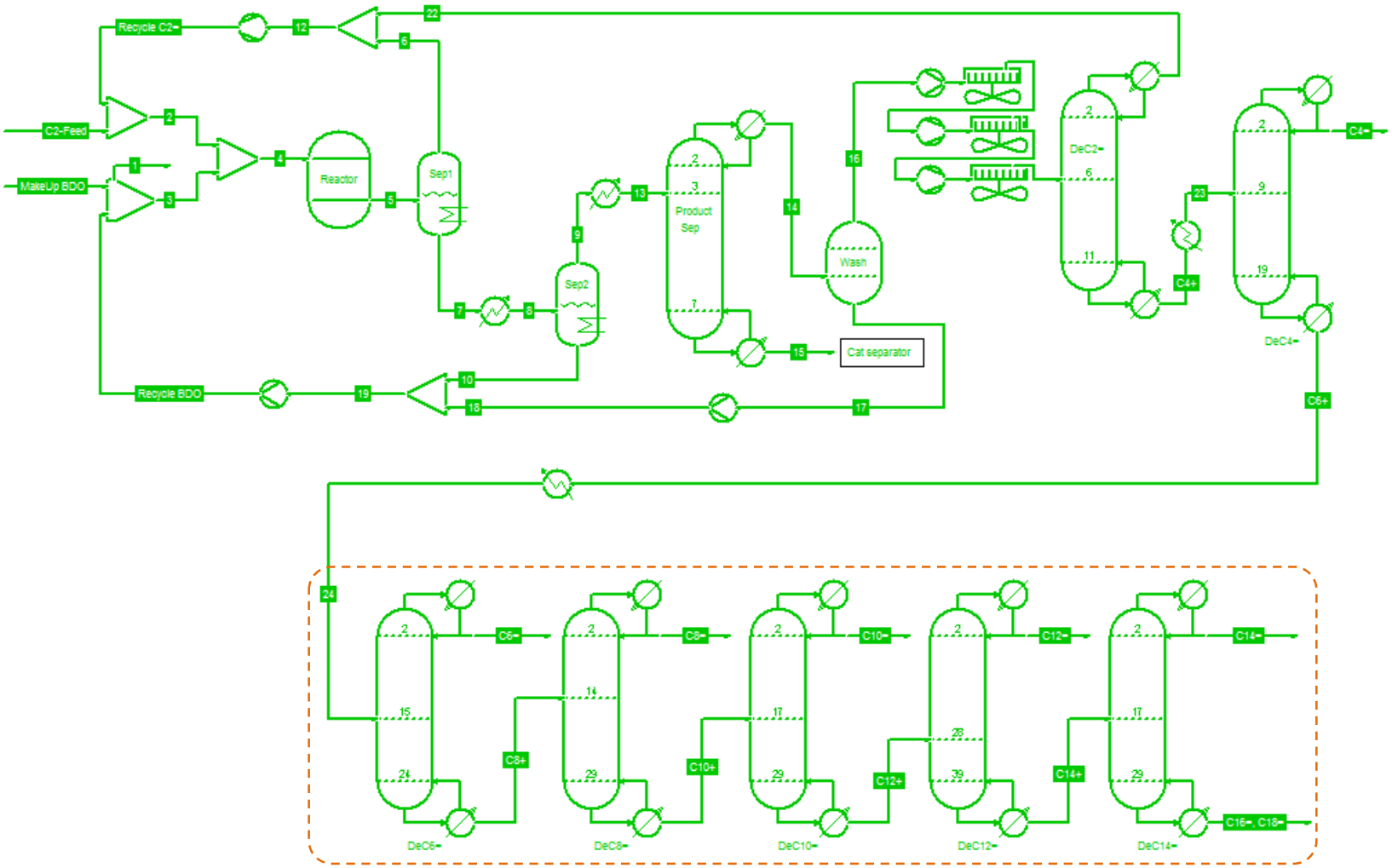


Icons show different DWCs in COCO (www.cocosimulator.com)

Flowsheet Simulation with CAPE-OPEN PCM

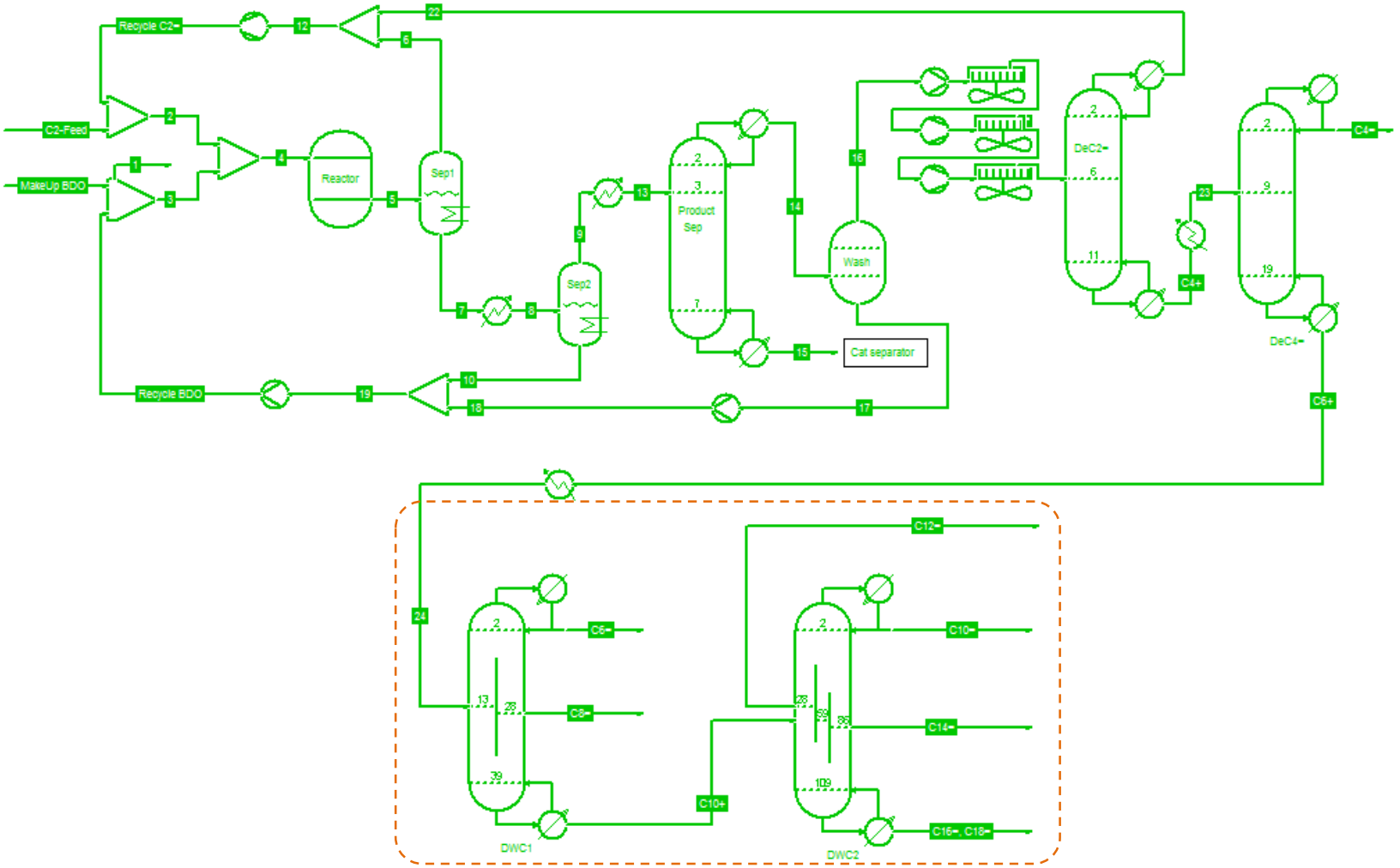
- Standard column model for CO compliant systems
- Flowsheet intensification with DWCs
- Easy column configuration with multiple walls
- Icons immediately reflect actual configuration
- Connection to vendor tools for easy detailed rating
- Rapid tray/packing internals design of each column section, with selection of any modern type separations internals
- Overall column sizing including feed inlets and draw-off trays
- CAPEX & OPEX estimates enables Total Annual Cost comparison

Flowsheet Intensification with DWCs - I



Separation using *Direct Sequence of Distillation Columns*

Flowsheet Intensification with DWCs - II



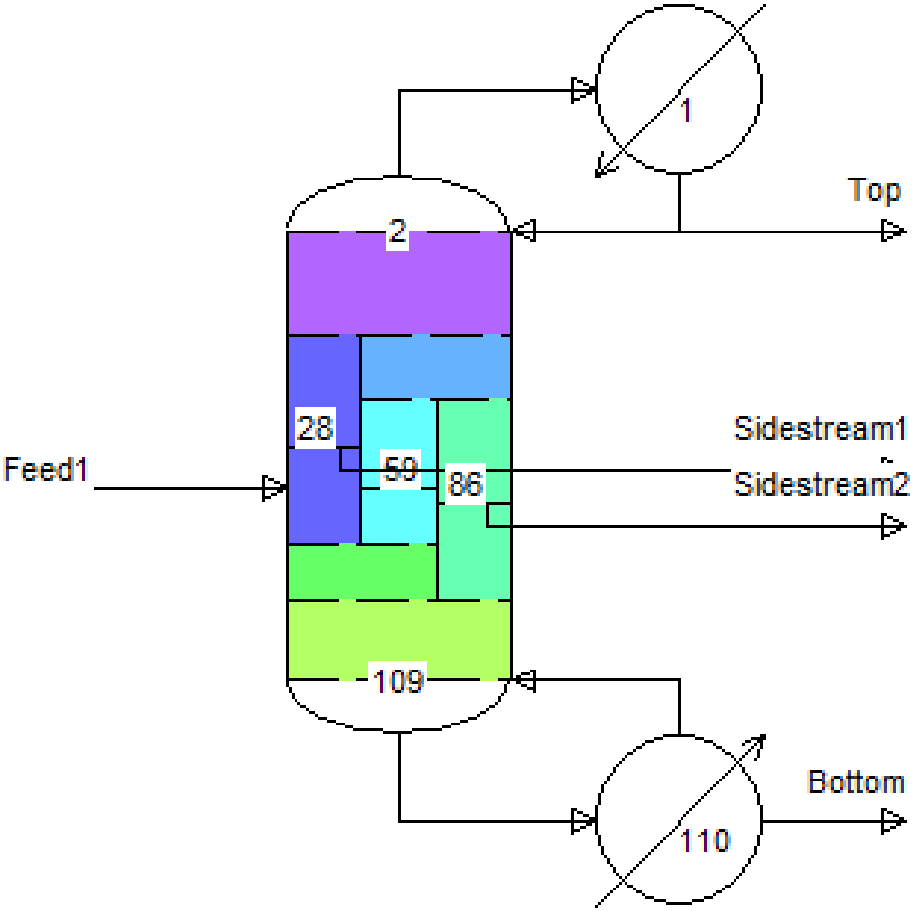
Separation using *Dividing Wall Columns*

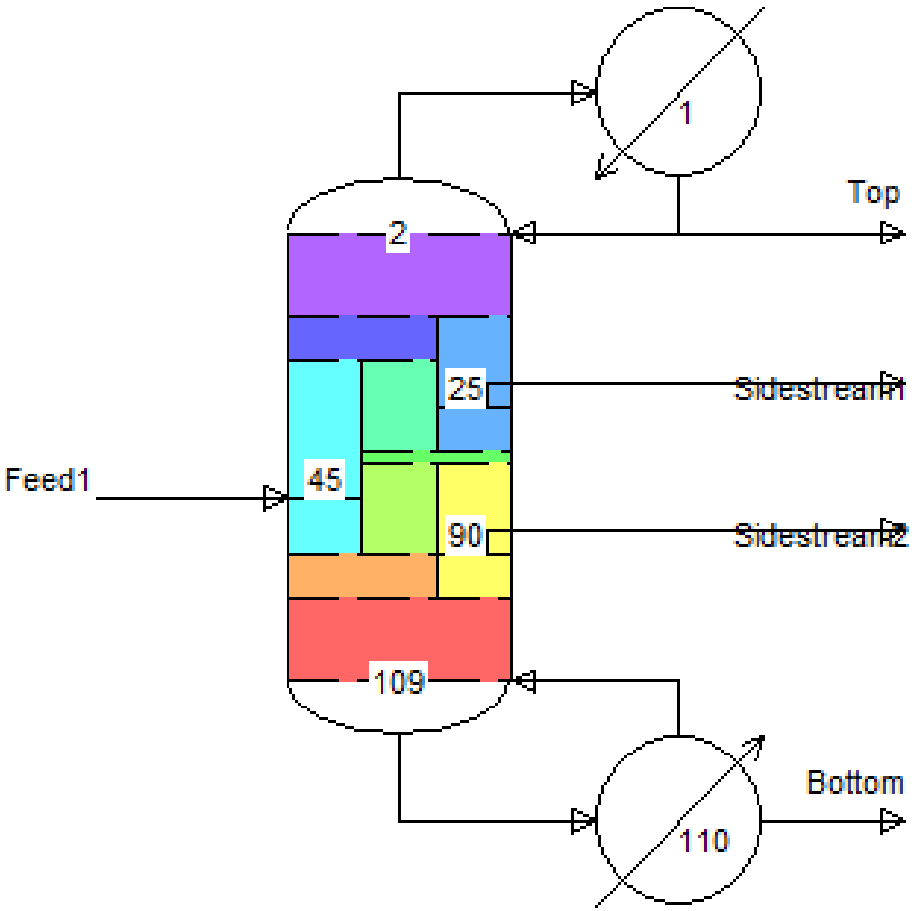
Flowsheet Intensification with DWCs - III

Movie

Easy Configuration with Multiple Walls

- Clear identification of column sections to guide engineer





Rate-Based Models

- Real distillation operations do not reach equilibrium
- Details of column internals are not always considered
- Heat transfer usually not included in simulation
- Column hydraulics are oversimplified (or ignored)

Rate-Based Parallel column Model

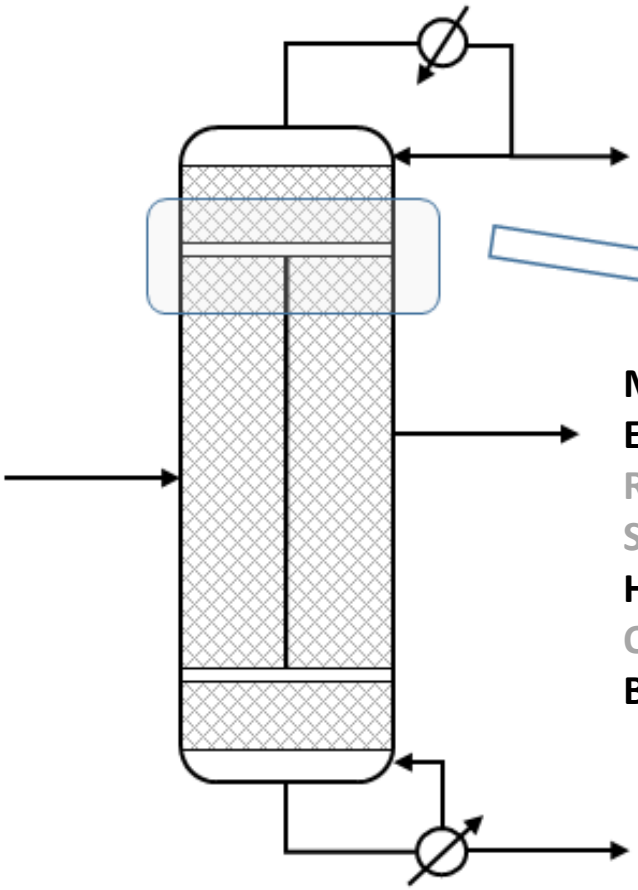
Rate-Based Models

Aspen Custom Modeler (ACM) Based Models

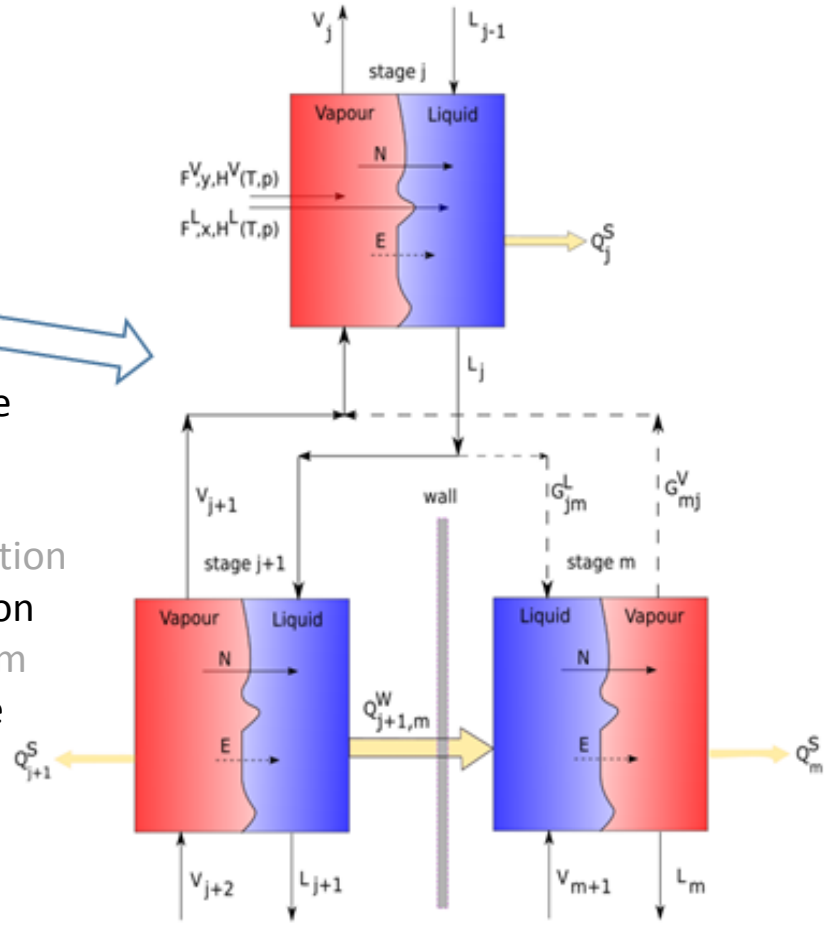
- Mueller, I., & Kenig, E. Y. Reactive distillation in a dividing wall column: rate-based modeling and simulation. *Industrial & engineering chemistry research.* 46(11), pp3709-3719, 2007
- Hiller, C., Buck, C., Ehlers, C., & Fieg, G. Nonequilibrium stage modelling of dividing wall columns and experimental validation. *Heat and mass transfer.* 46(10), pp1209-1220, 2010

ACM cannot be used to model DWCs with changed configuration without remaking the model

Rate-Based Parallel Column Model



M: material balance
E: energy balance
R: rate equation
S: summation equation
H: hydraulic equation
Q: phase equilibrium
B: pressure balance

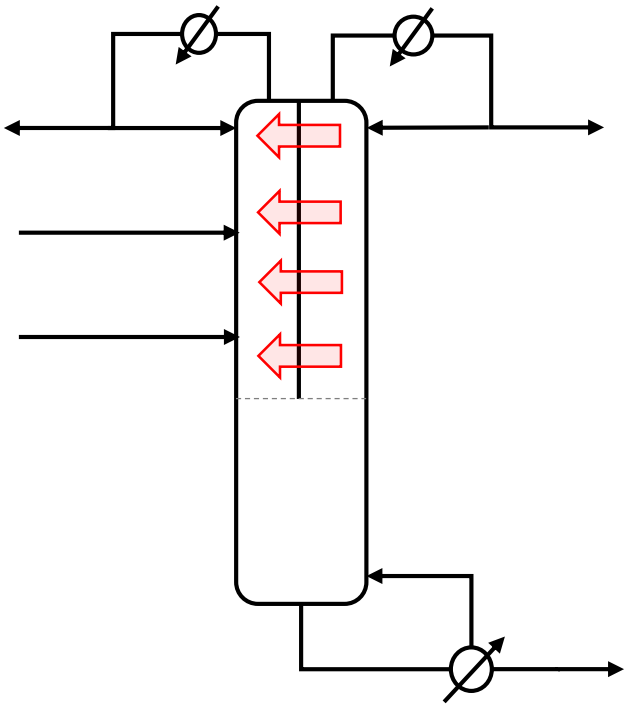


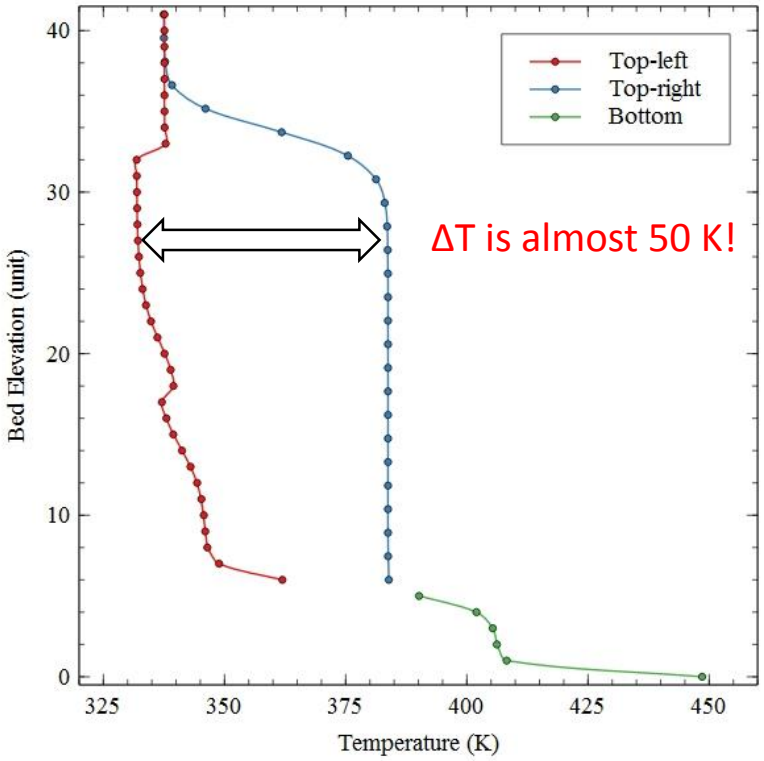
Conventional Column: Stages are adjacent AND in sequence
DWCs: Stages are adjacent but all are NOT in sequence

Equations solved simultaneously using Newton's method

Heat Transfer across Dividing Walls

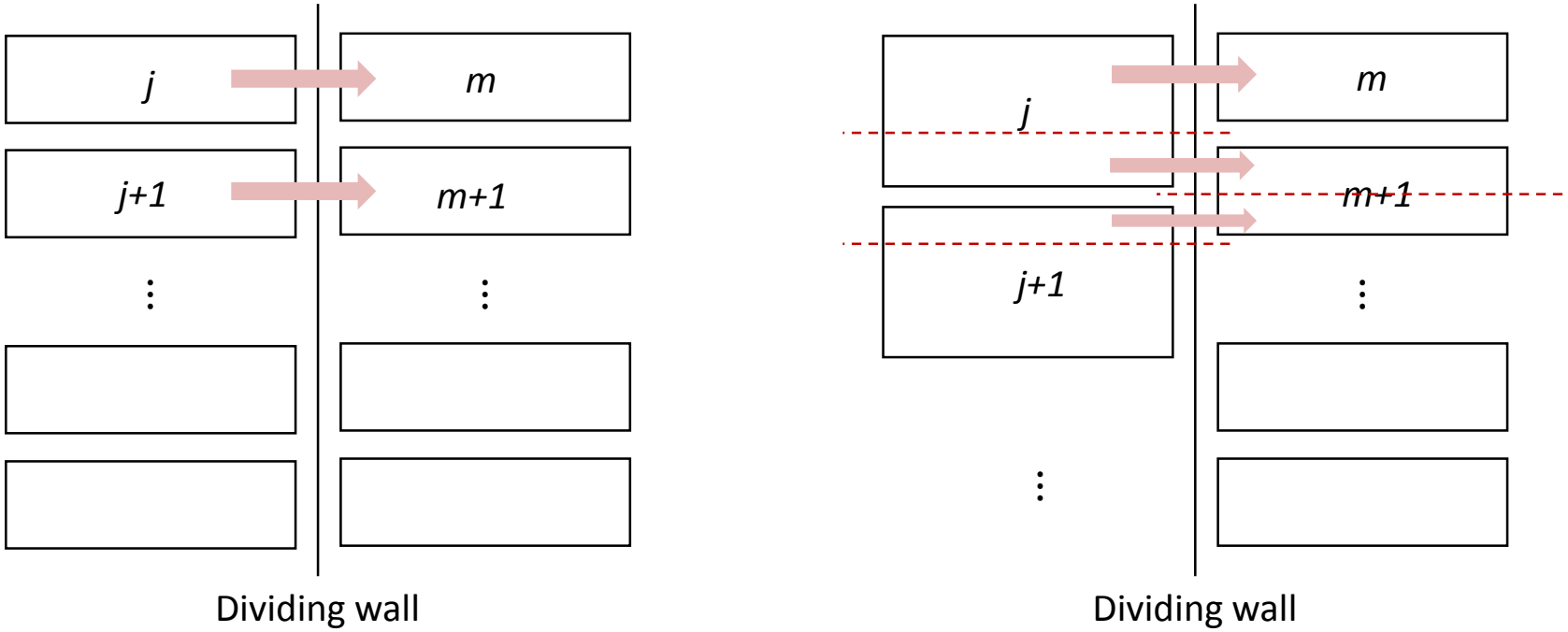
- Dividing walls are not insulators
- Temperature gradients can be significant
- Can be important for small columns (often used in experimental studies)
- Extremely difficult to include heat transfer in multi-column models
- Very easy to include heat transfer in Parallel Column Model





Heat Transfer across Dividing Walls

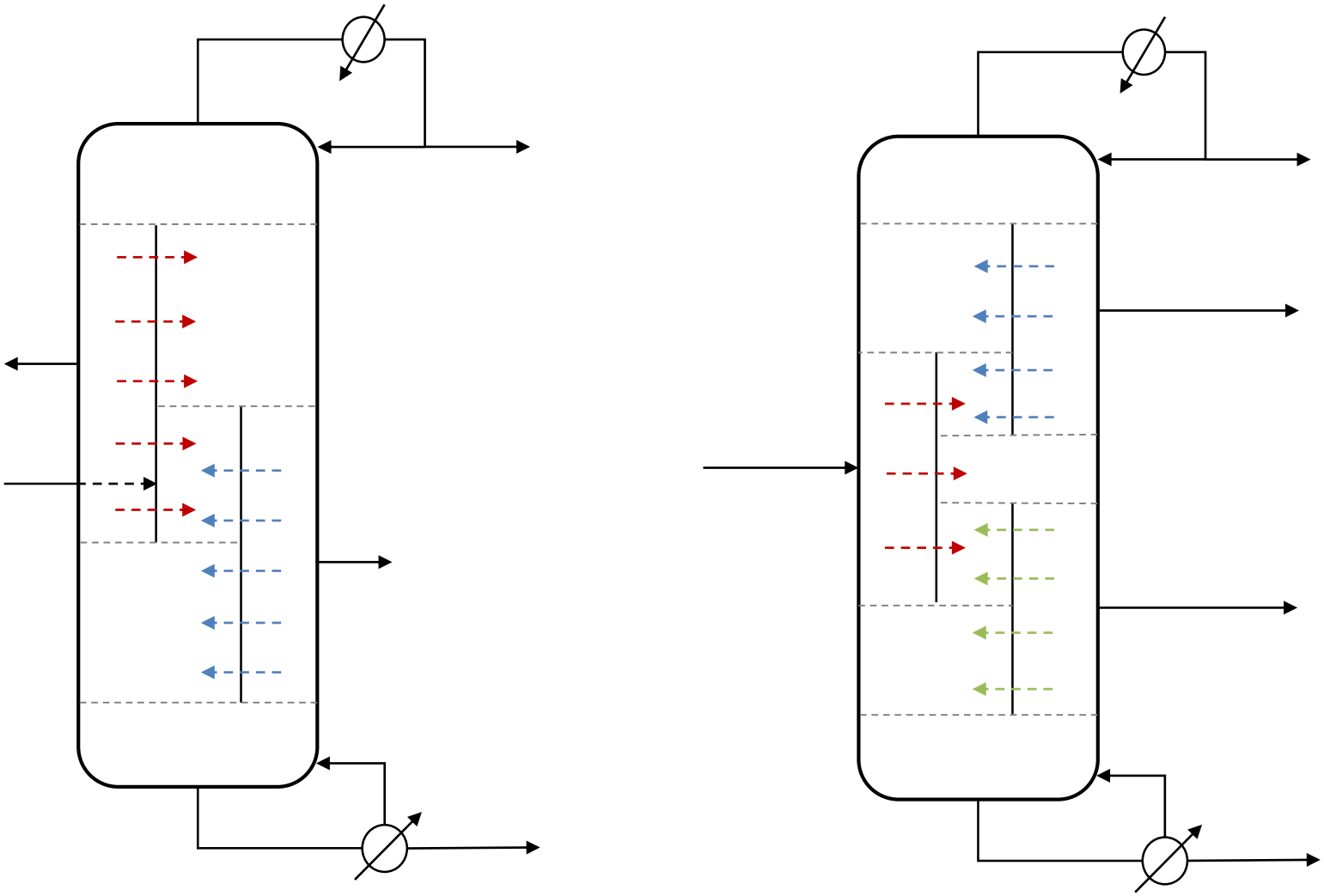
- Number of stages may not align



- Need to account for appropriate heat transfer area for each stage
- Need multiple heat transfer terms for asymmetric walls

Heat Transfer across Dividing Walls

- Multiple walls



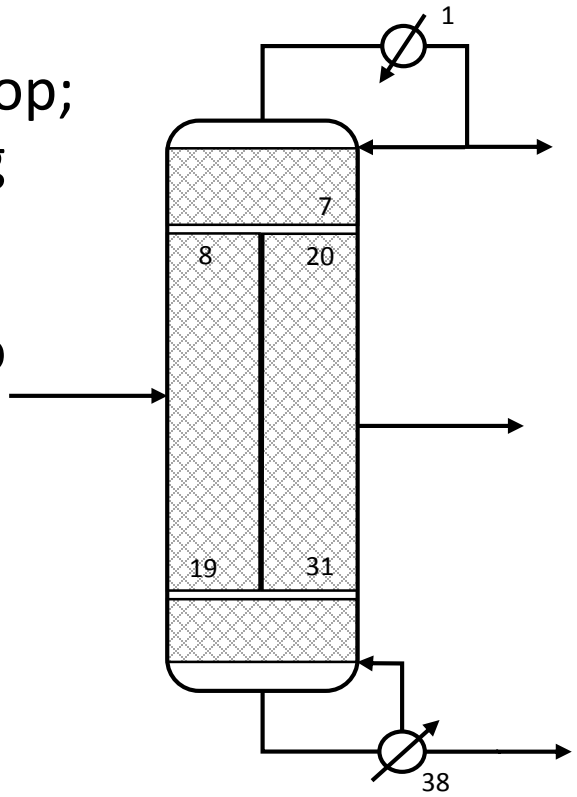
Validation: Experiments of Bailee Roach

- Data in recent Ph.D. thesis from The University of Texas at Austin
- Two systems investigated:
  - Alcohol System (1-hexanol, 1-octanol, 1-decanol)
  - Hydrocarbon System (1-pentane, cyclohexane, 1-heptane)

Roach, B. J. (2017). *A design model for dividing wall distillation columns* (Doctoral dissertation).

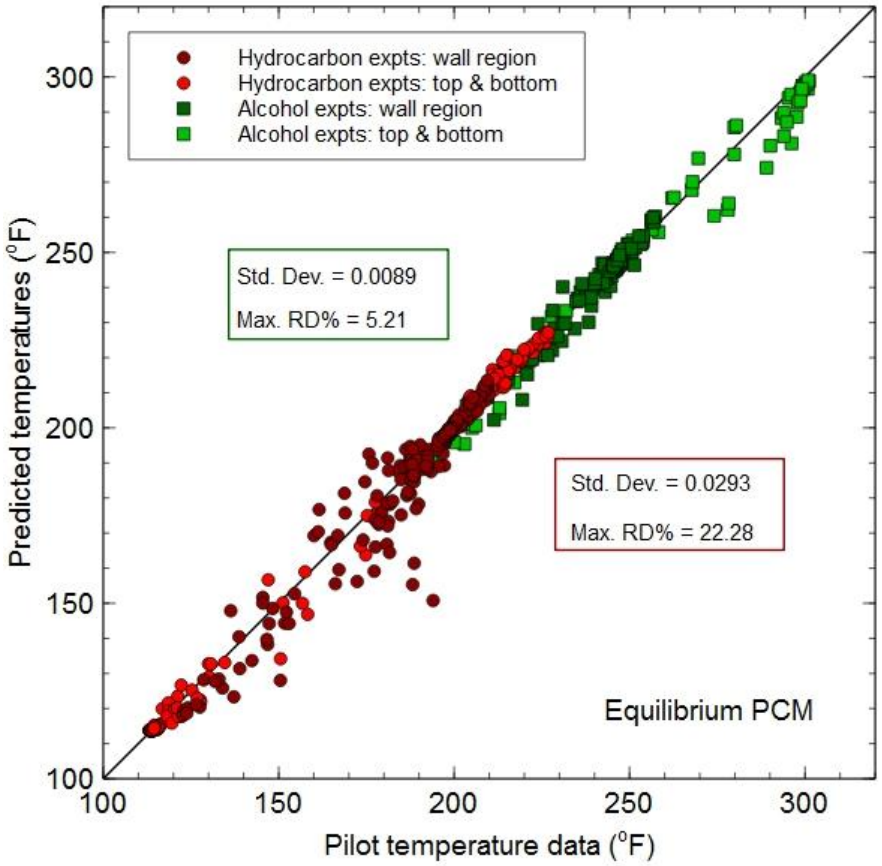
Validation: Experiments of Bailee Roach

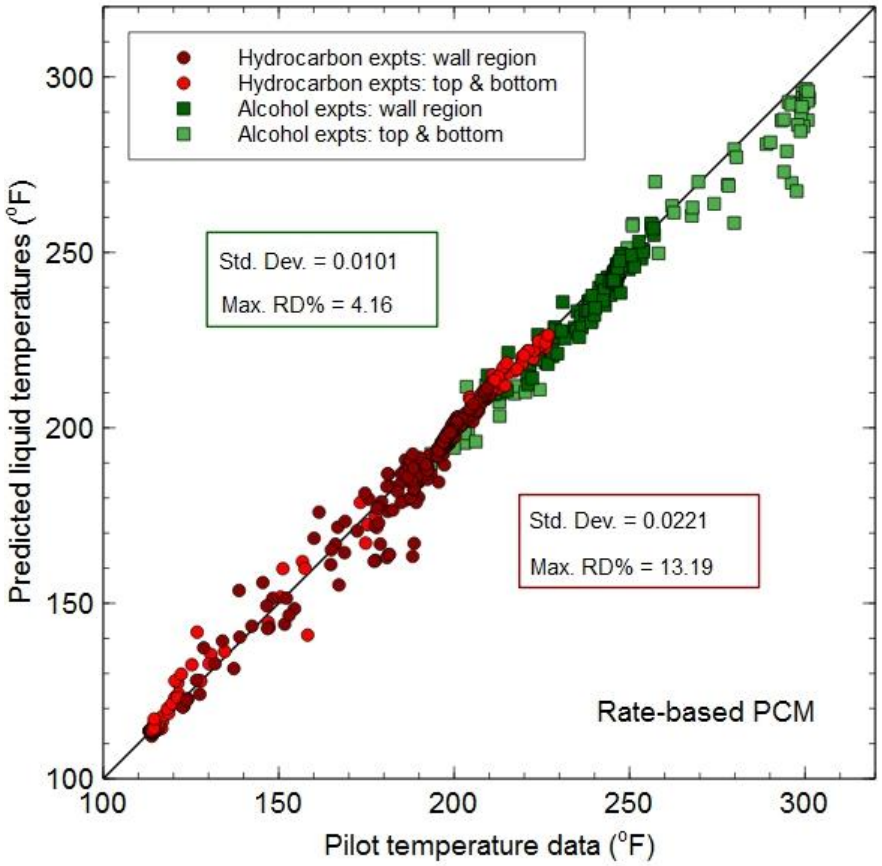
- Column dimensions (from Roach, 2017)
  - Sulzer MellaPak 500Y corrugated metal sheets
  - HETP is given by Sulzer as 9.5 inches/stage
  - Outer column diameter is 6.63 inches
  - Wall is located in the middle of column shell
- *Kooijman et al. (2002)* model for pressure drop; Vapor split ratios are estimated by equalizing the pressures on two sides of the wall
- Heat transfer across the wall and heat loss to the surroundings are considered
- Hybrid MTC model
  - k_G: Rocha et al. (1996)
  - k_L: Song correlation
  - a_e: Wang form of Tsai correlation



Validation: Experiments of Bailee Roach

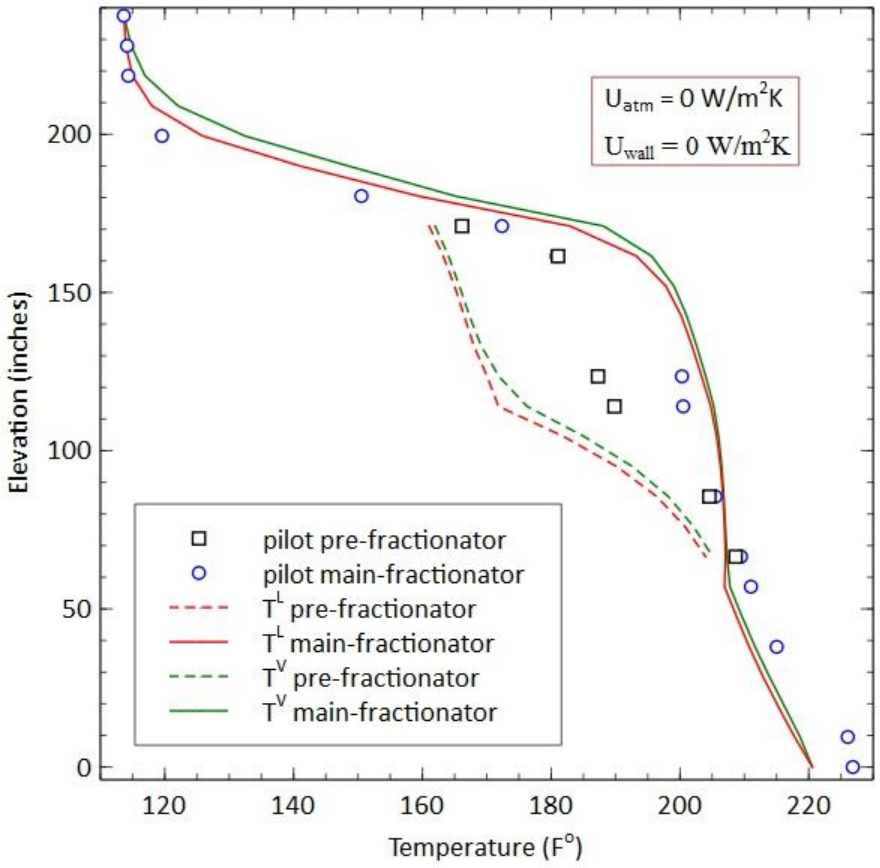
- All experiments from Roach (2017) modeled with PCM

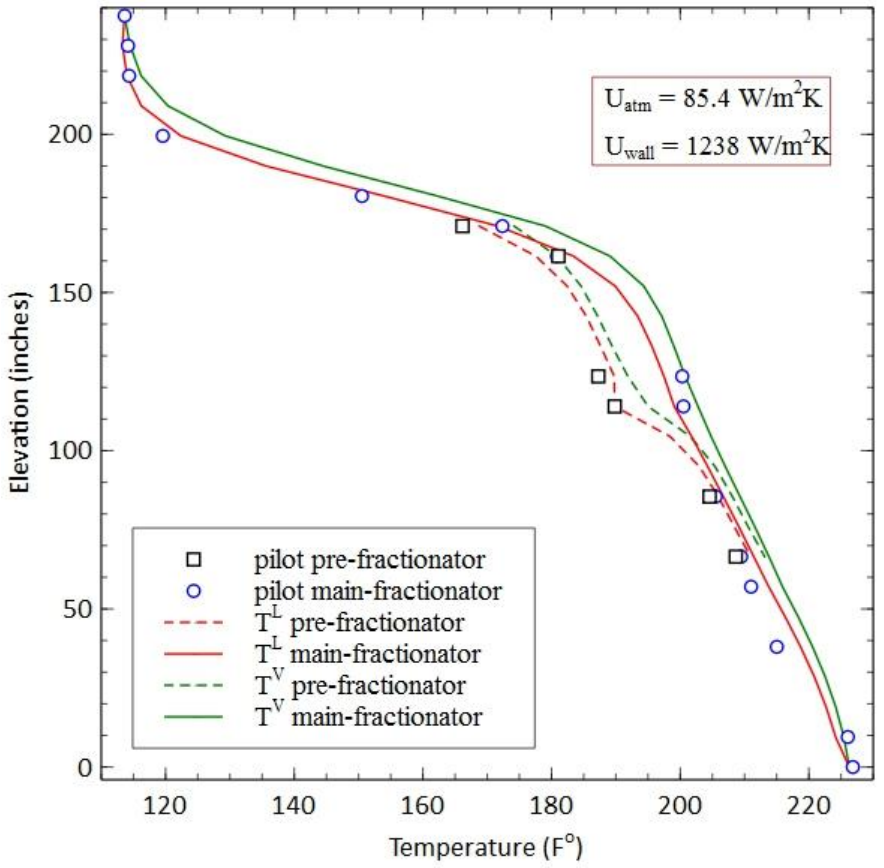




Heat Transfer Important in Small Columns

- Case H12: Hydrocarbon Equimolar Feed from Roach (2017)





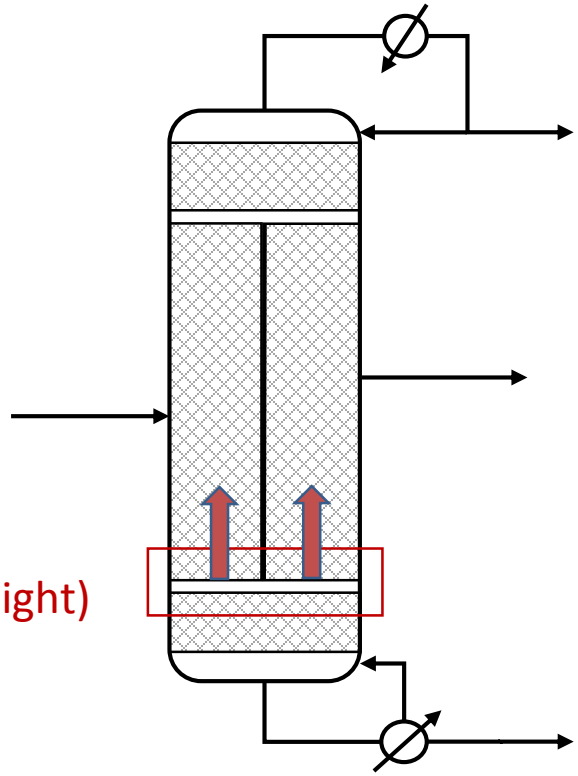
Auto-Adjusted Vapor Split

Pressure **B**alance equation (*B equation*)

$$B \equiv \Delta p^{W}_{left} - \Delta p^{W}_{right} = 0$$

Each B equation corresponds to one extra variable, vapor split ratio β

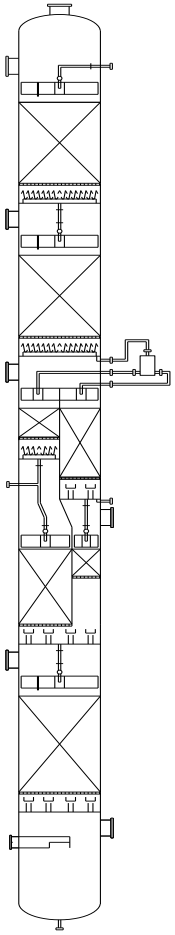
β = Vapor Left / (Vapor Left + Vapor Right)



Pressure equalization is achieved by adjusting β during the simulation

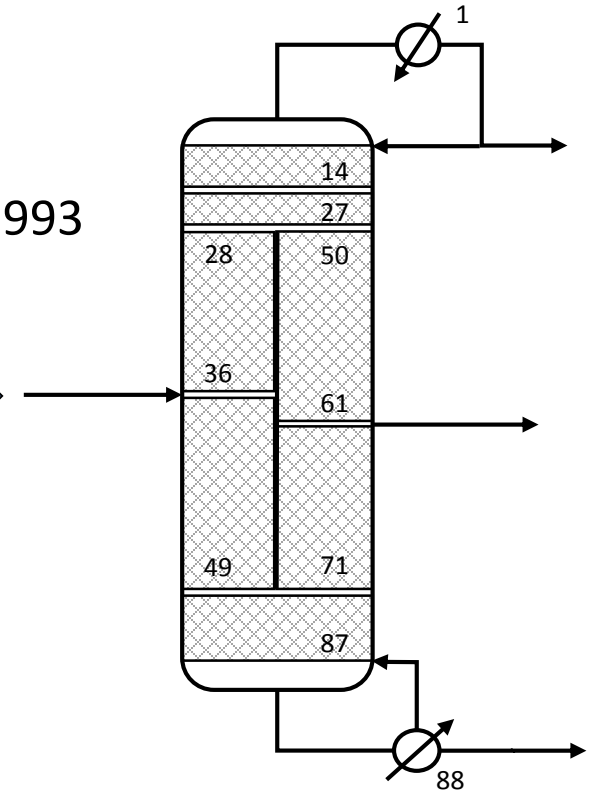
Auto-Adjusted Vapor Split: Dejanović Column

- Aromatics DWC



- Pressure drop model: Rocha-Bravo-Fair 1993

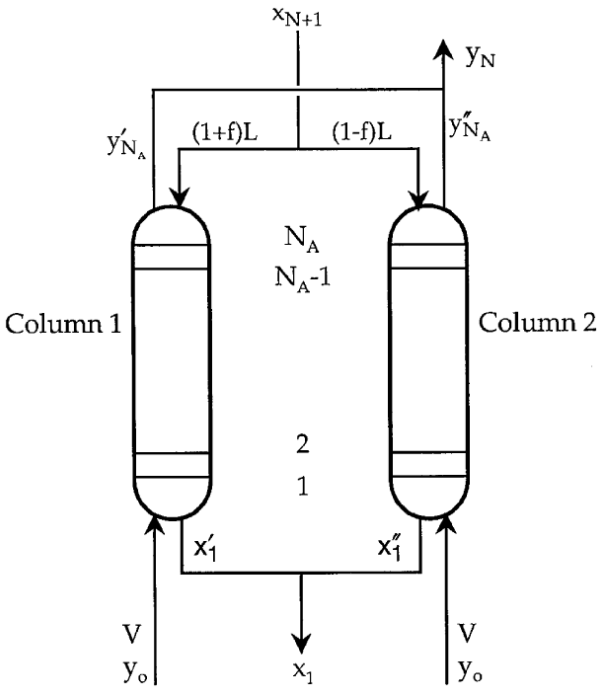
- Vapor Split:
  - **Dejanović et al. (2011)** **0.6639**
  - **ChemSep PCM estimate** **0.6568**



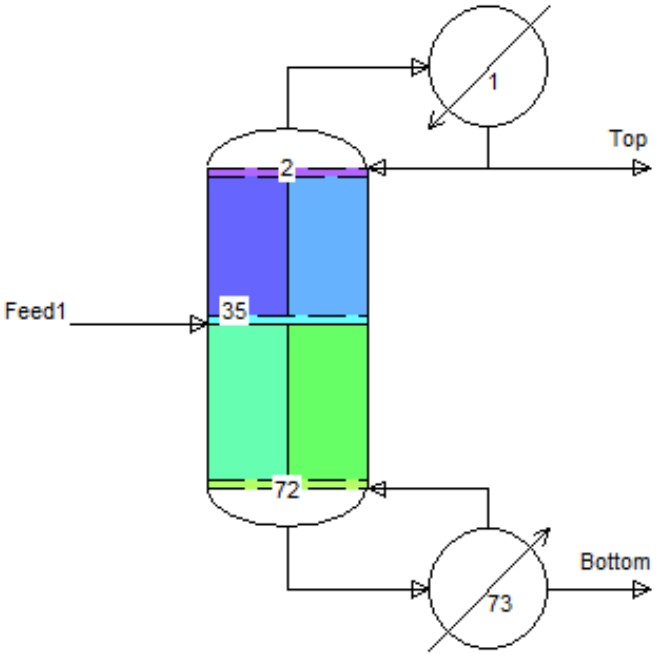
Dejanovic, I., Matijašević, L., Jansen, H., & Olujic, Z. (2011). Designing a packed dividing wall column for an aromatics processing plant. *Industrial & Engineering Chemistry Research*, **50**(9), 5680-5692.

Maldistribution Simulation with PCM

Billingham and Lockett Maldistribution Model



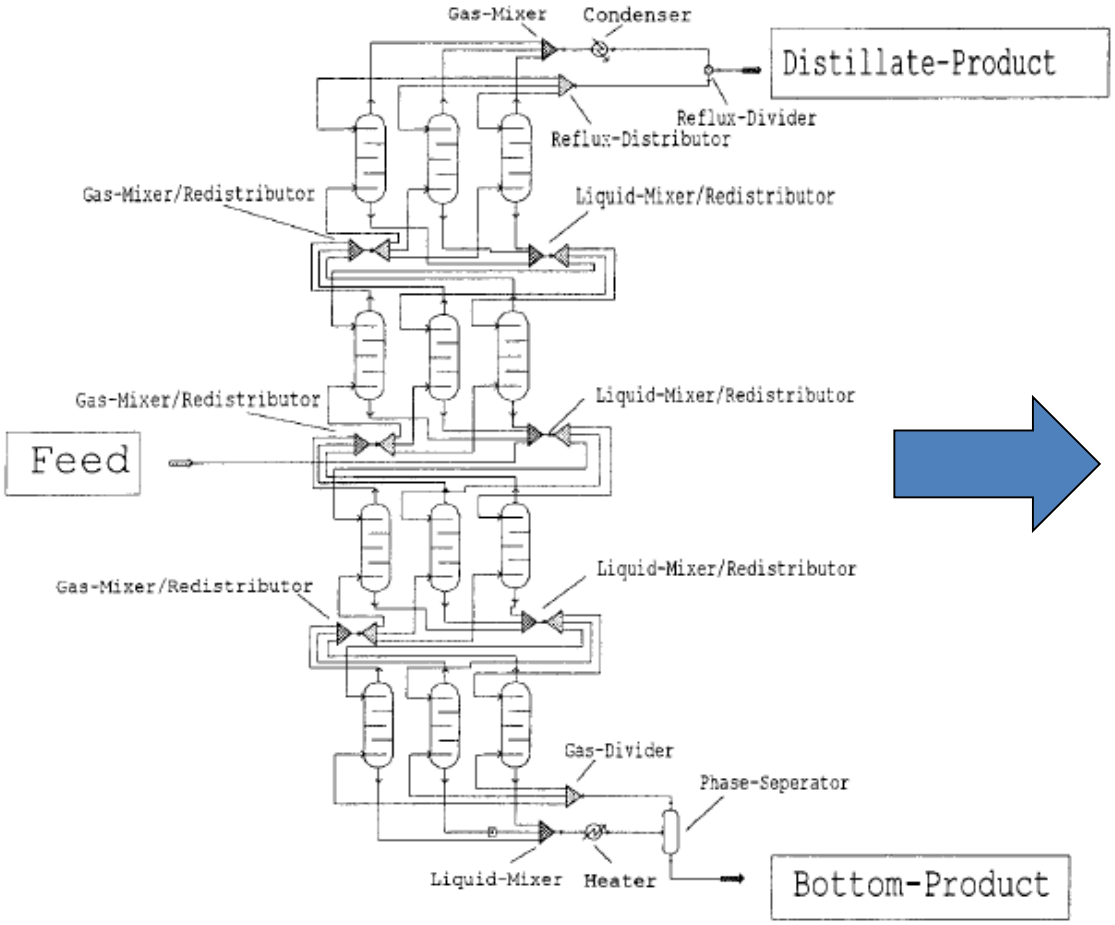
Equivalent PCM Structure



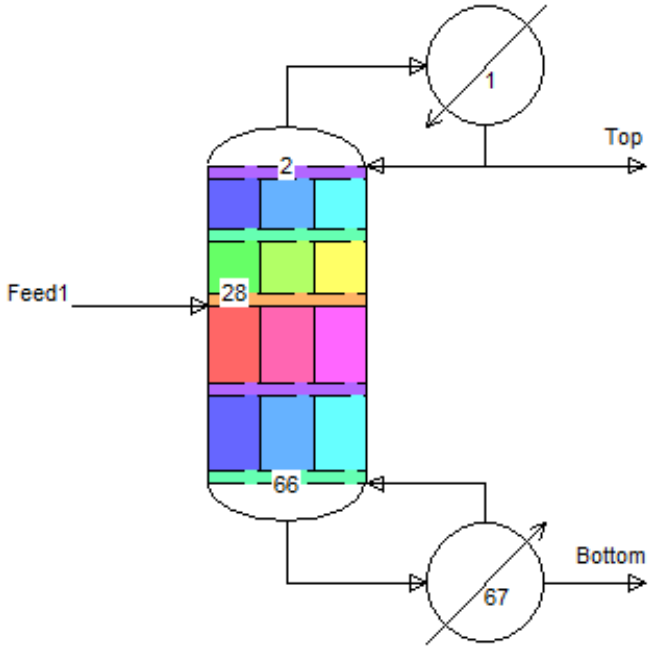
- Redistributors modeled as stages with no mass transfer

Maldistribution Simulation with PCM

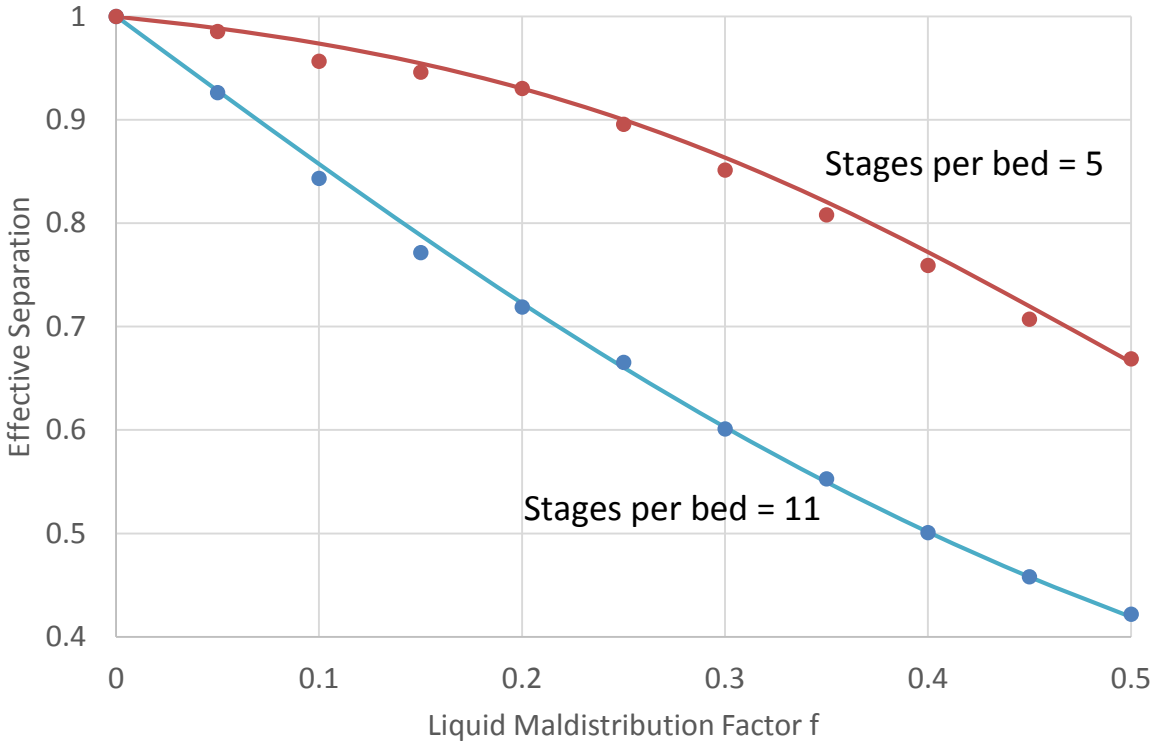
Schultes Maldistribution Model



Equivalent PCM Structure



Maldistribution Simulation with PCM



$$Effective\ Separation = \frac{Number\ of\ stages\ without\ maldistribution}{Number\ of\ stages\ with\ maldistribution}$$

Fractional effective separation as interpolated from the top distillate compositions
Significant influence of the number of redistributors

Conclusions

- The rate-based PCM
  - Takes very little effort to set up a DWC column model
  - Requires no initial guesses from engineer
  - Converges much quicker than multi-column models for DWCs
  - Makes it very easy to account for heat transfer across walls
  - Vapor split can be calculated (not specified)
  - Can be used to model maldistribution in packed columns
- **Rapid design and optimization of DWC columns**
- Rate-based PCM in good agreement with pilot plant data
- Experiments in DWC excellent test of k_L, k_G, and ΔP models
- For more on DWCs visit our poster on Monday evening