Improvements in Distillation Design

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Dan Summers | May 24, 2012

What is Distillation?

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Distillation is purification of gases or liquids by "playing" with their boiling points.

The earliest known distillation was between ethanol and water

What is Distillation?

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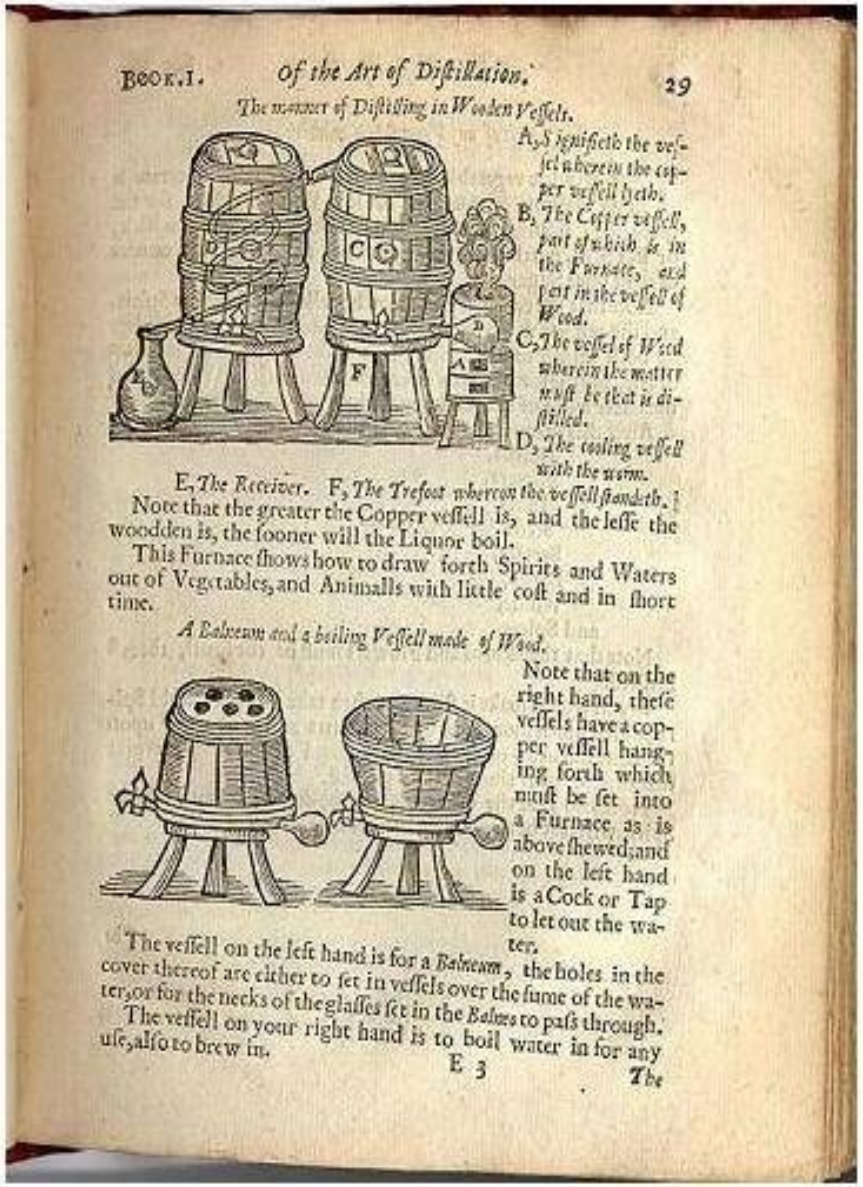

BOOK. I. *Of the Art of Diſtillation.* 29

The manner of Diſtilling in Wooden veſſels.

A, ſignifieth the veſſel wherein the copper veſſell ſtands.

B, The Copper veſſell, part of which is in the Furnace, and part in the veſſell of Wood.

C, The veſſel of Wood wherein the matter muſt be that is diſtilled.

D, The cooling veſſell with the worm.

E, The Receiver. F, The Trefoot whereon the veſſell ſtandeth.

Note that the greater the Copper veſſell is, and the leſſe the woodden is, the ſooner will the Liquor boil.

This Furnace ſhows how to draw forth Spirits and Waters out of Vegetables, and Animalls with little coſt and in ſhort time.

A Balneum and a boiling Veſſell made of Wood.

Note that on the right hand, theſe veſſels have a copper veſſell hanging forth which muſt be ſet into a Furnace, as is above ſhewed; and on the left hand is a Cock or Tap to let out the water.

The veſſell on the left hand is for a *Balneum*, the holes in the cover thereof are either to ſet in veſſels over the fume of the water, or for the necks of the glaſſes ſet in the *Balneo* to paſs through.

The veſſell on your right hand is to boil water in for any uſe, alſo to brew in.

E 3 *The*

The Art of Distillation by John French 1651

What is Distillation?

"Strong Drink" (different than wine) mentioned in Old Testament nearly 20 times. People believe that some of these passages were written nearly 3500 years ago or 1500 BC.

From Wikipedia you can find, "Distillation is a very old technique which was used by the Chinese in 3000 years BC."

I contend that Distillation must have preceded the more commonly referred to "World's Oldest Profession." (This is because the more common one wasn't really a profession until people realized it was wrong.)

What is Distillation?

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Early Distillation was typically a single stage – or more simply a pot boiling with a condenser.

What is Distillation?

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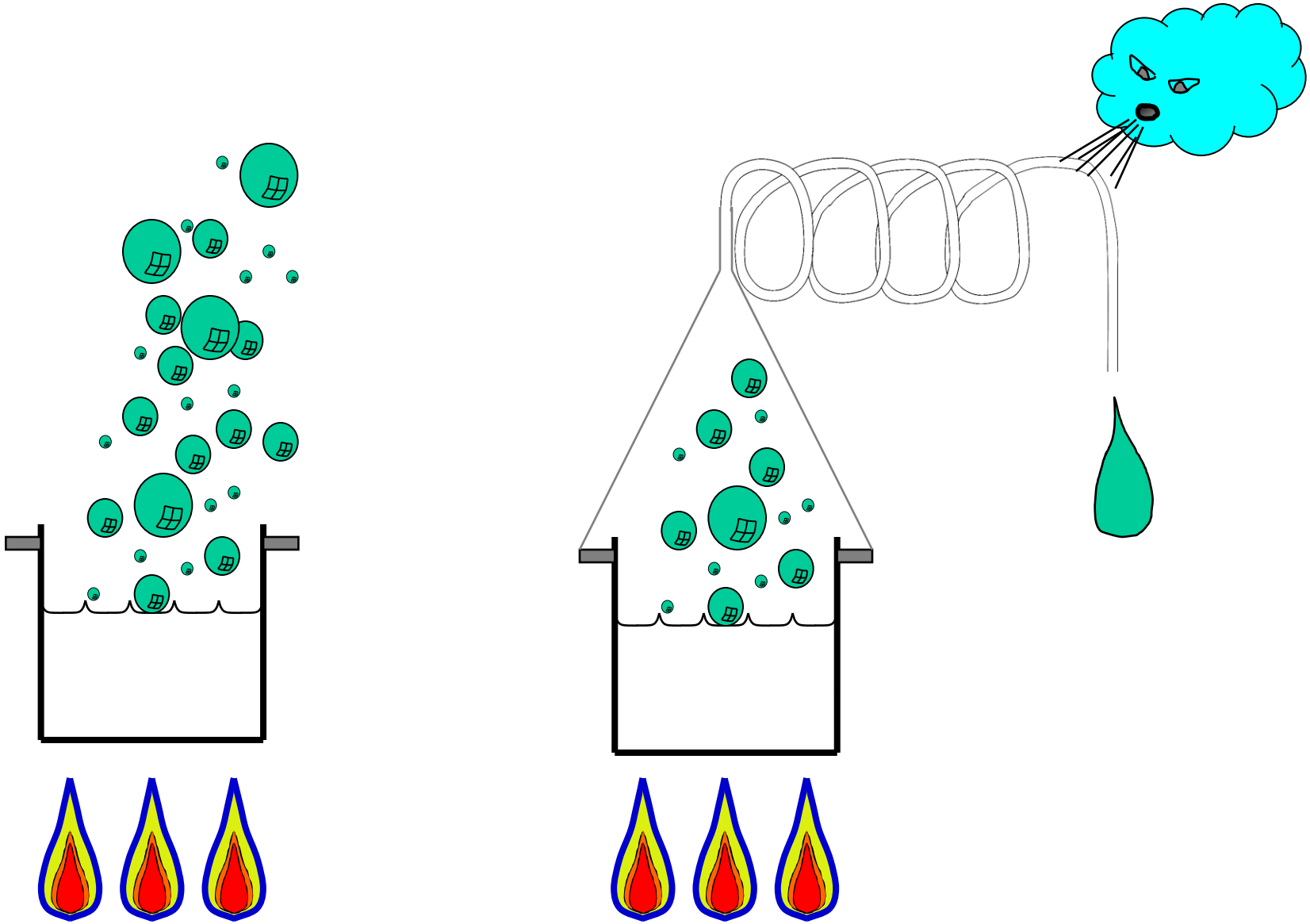

What is Distillation?

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The composition of the overhead condensed vapors was found to have a much higher concentration of the lighter component.

For example, a boiling pot of 6 to 8% ethanol has about 40% ethanol (80 proof) in the condensed vapors.

Ethanol and Water

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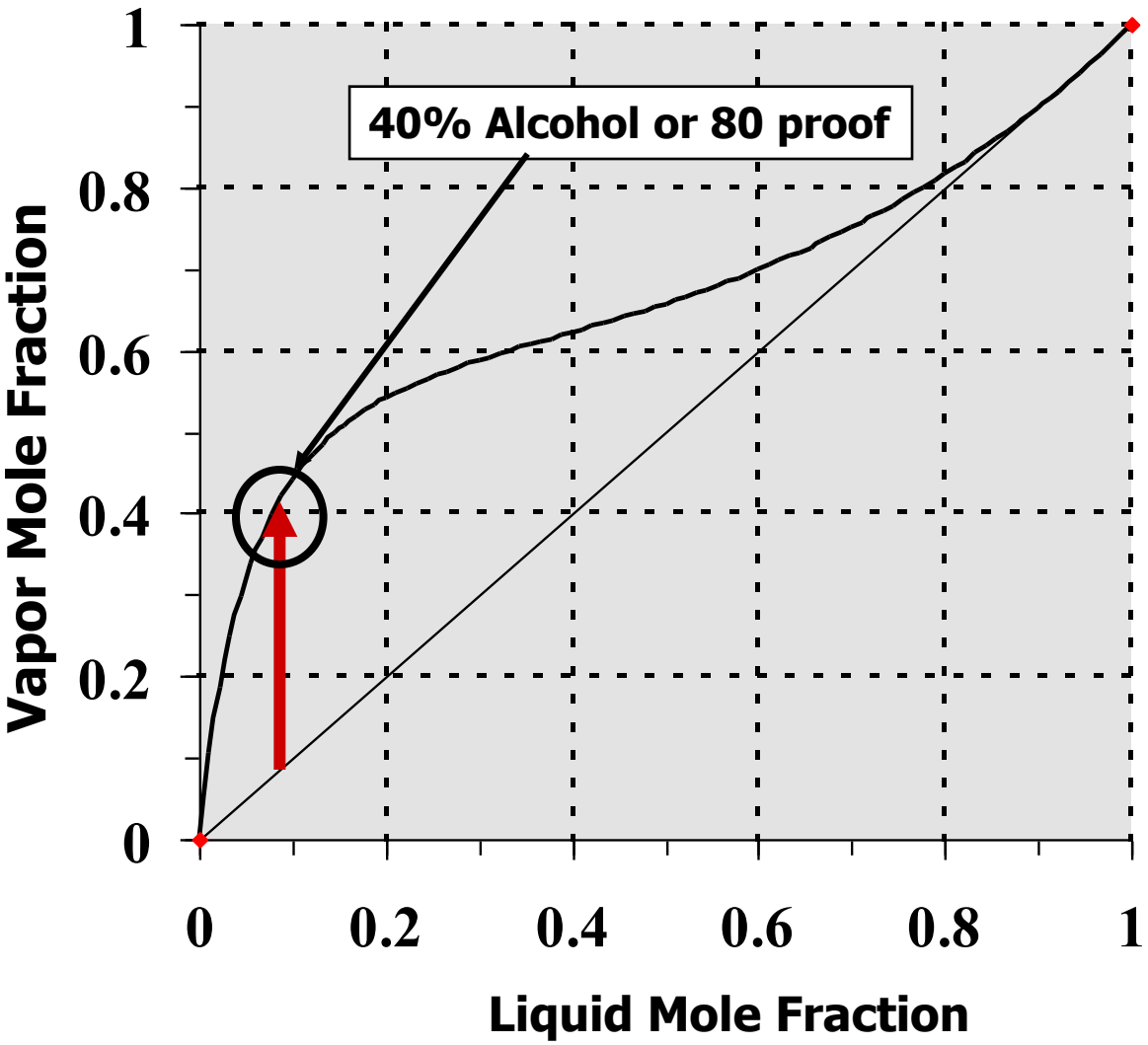

Pressure = 1 atm

What if you do this twice?

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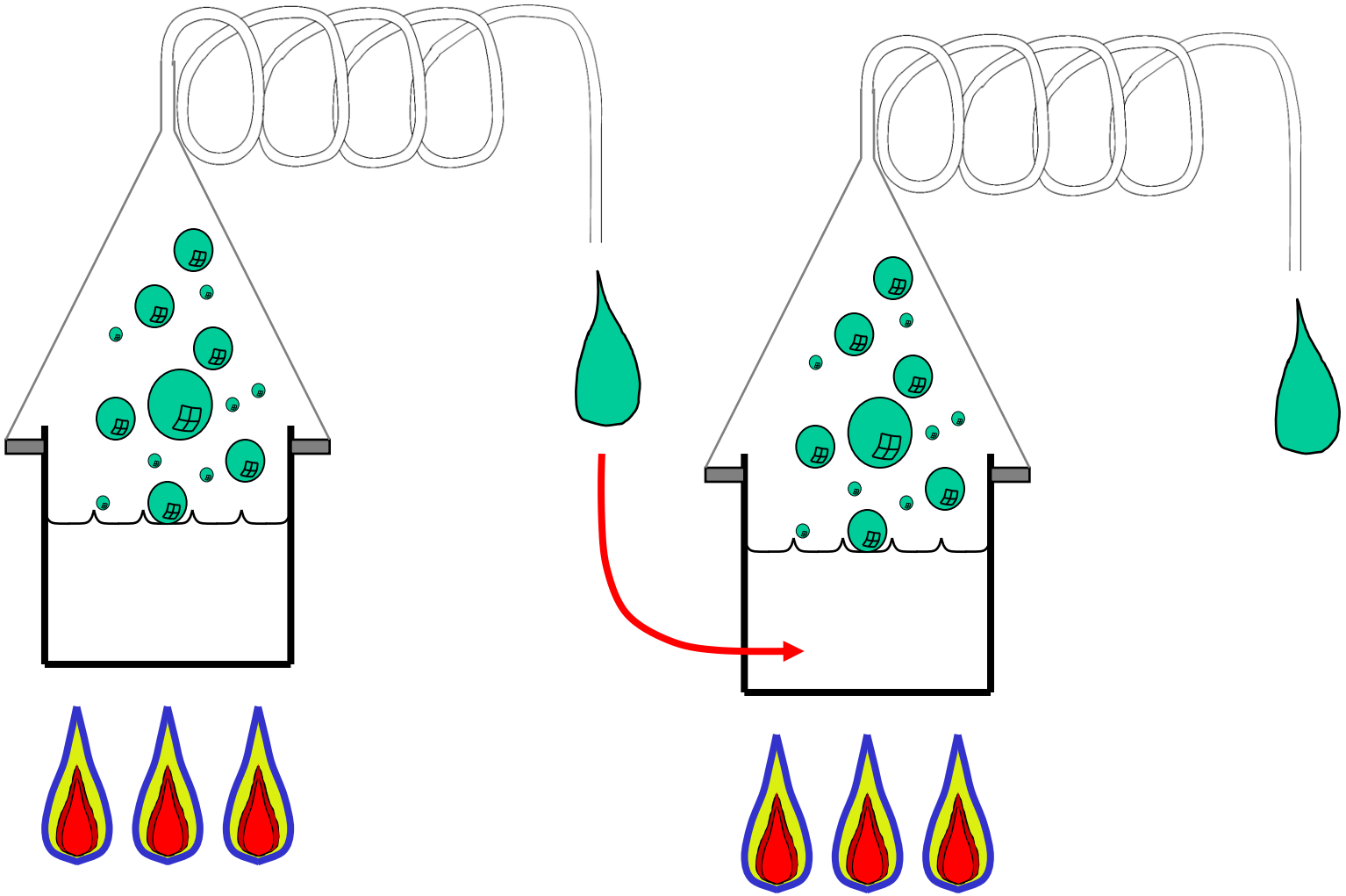

62% Ethanol!

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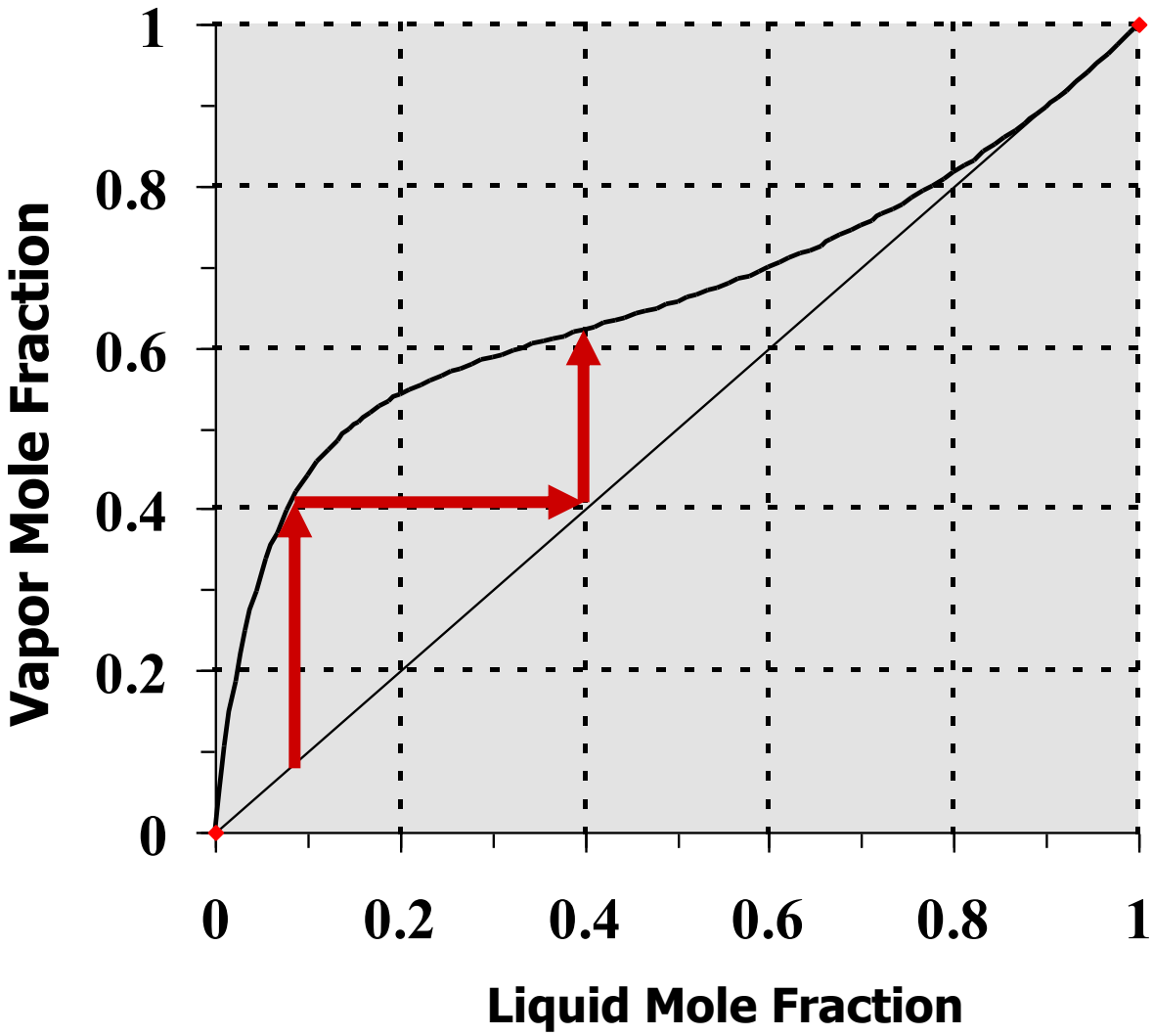

To make cognac you distill twice

Pressure = 1 atm

How about 3 times or More?

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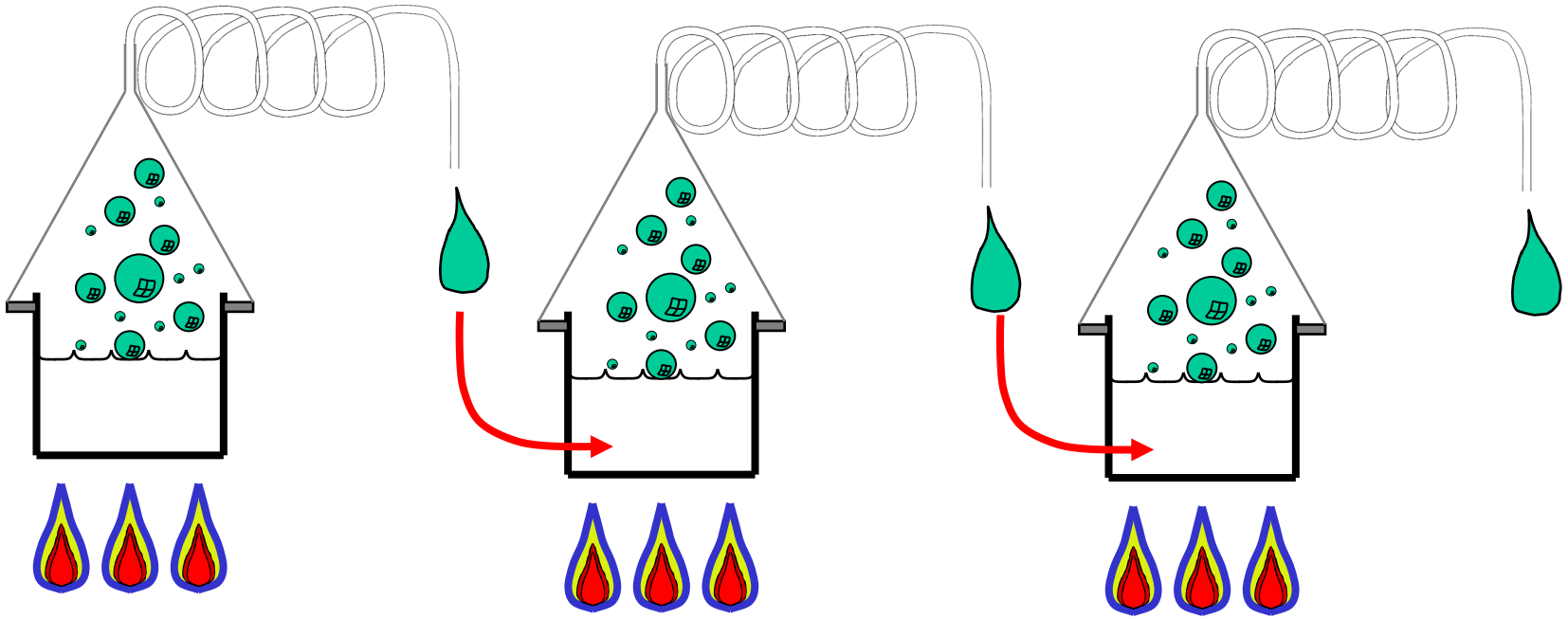

You get 70% Ethanol!

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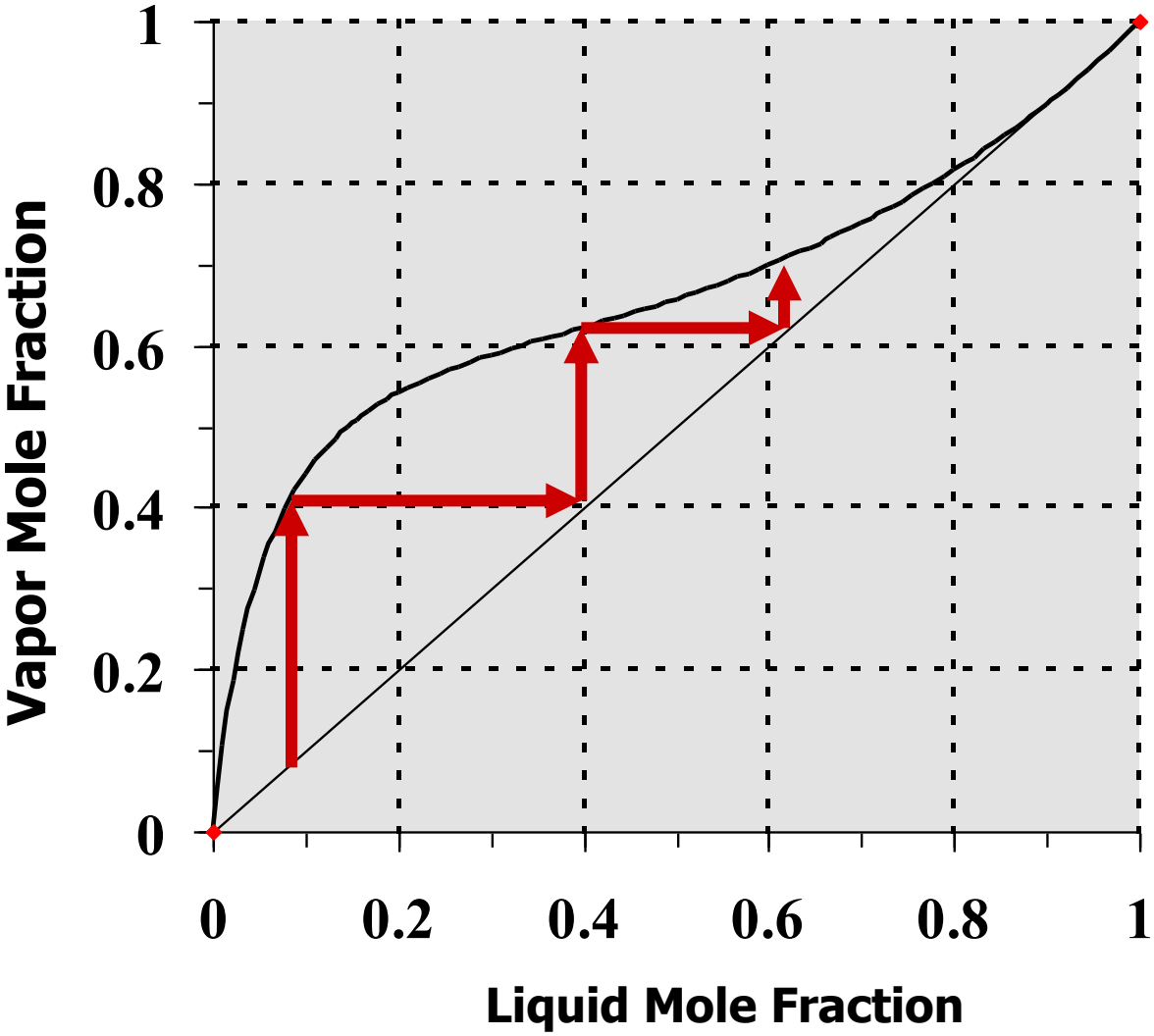

Pressure = 1 atm

If you turn this into Column with Reflux

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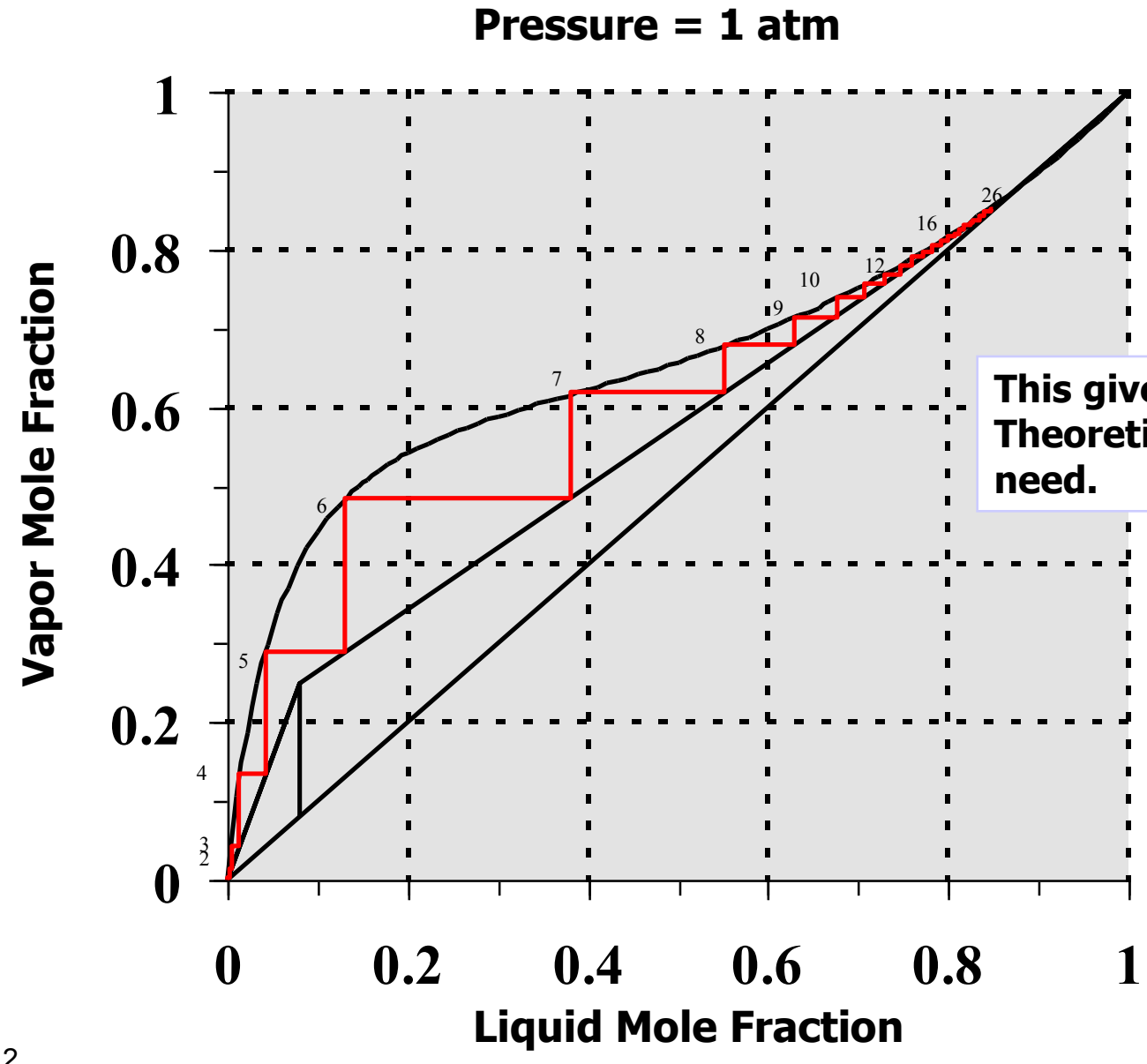

This gives us the Theoretical Stages we need.

Mass Transfer

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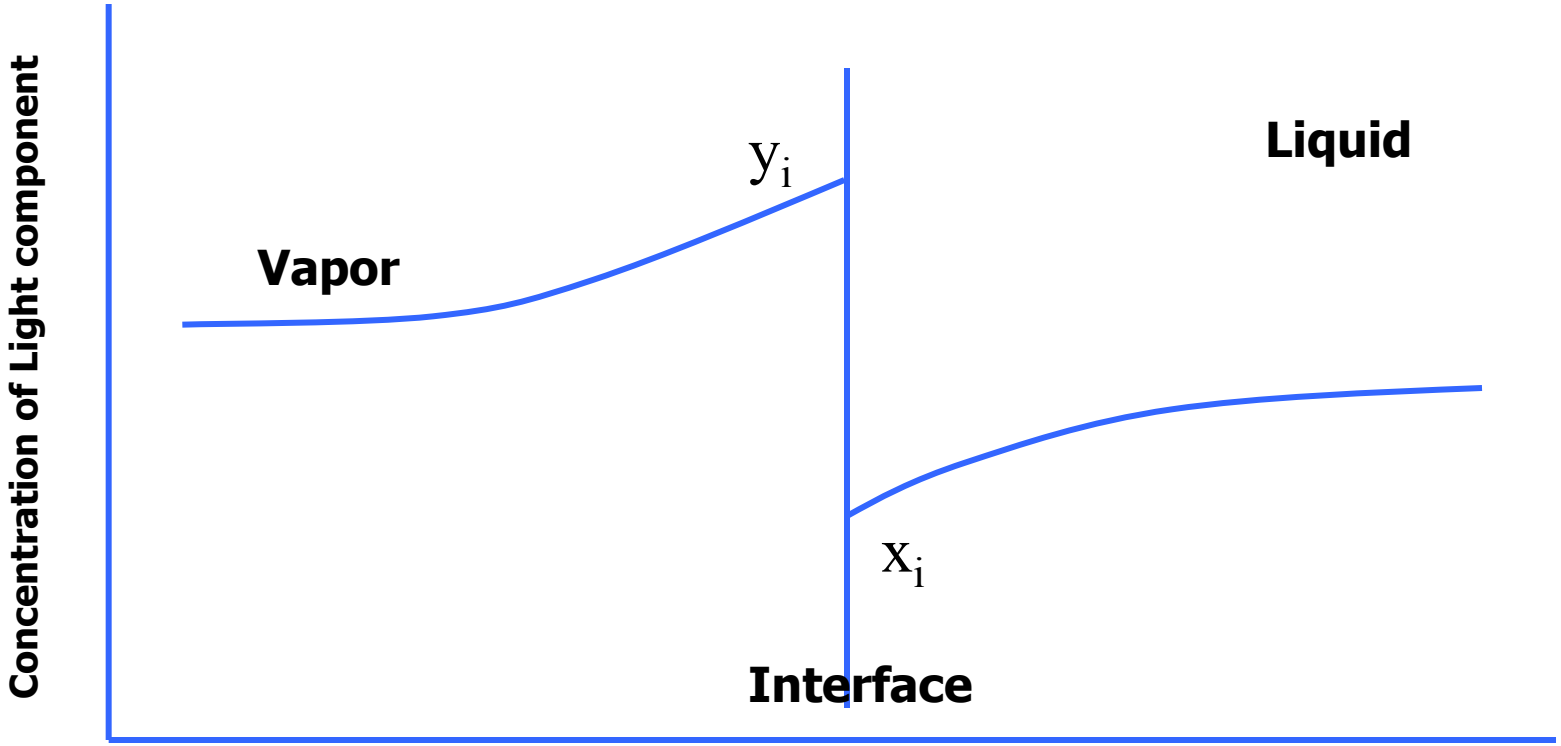
The "Gory Details" are that mass transfer only occurs at the interface between the liquid and vapor phase. In a trayed tower this occurs at the bubble wall, in a packed tower this occurs at the thin film.



Basic Process Considerations

Distillation is:

The most common separation technique practiced today.

It consumes enormous amounts of energy in both heating and cooling.

Can contribute to more than 50% of a plant's operating costs.

Has been the focus of numerous studies by the US DOE for over 30 years to reduce energy consumption.

Simulation Tools

Simulation Tools do little more than what the previous McCabe-Thiele diagram did except add in Heat effect and how to handle multicomponent mixtures.

The key to a good simulation is getting the equilibrium data correct. The set of Equilibrium data is called a Model

Simulations

Most Critical Aspect of Distillation Technology !

Simulations

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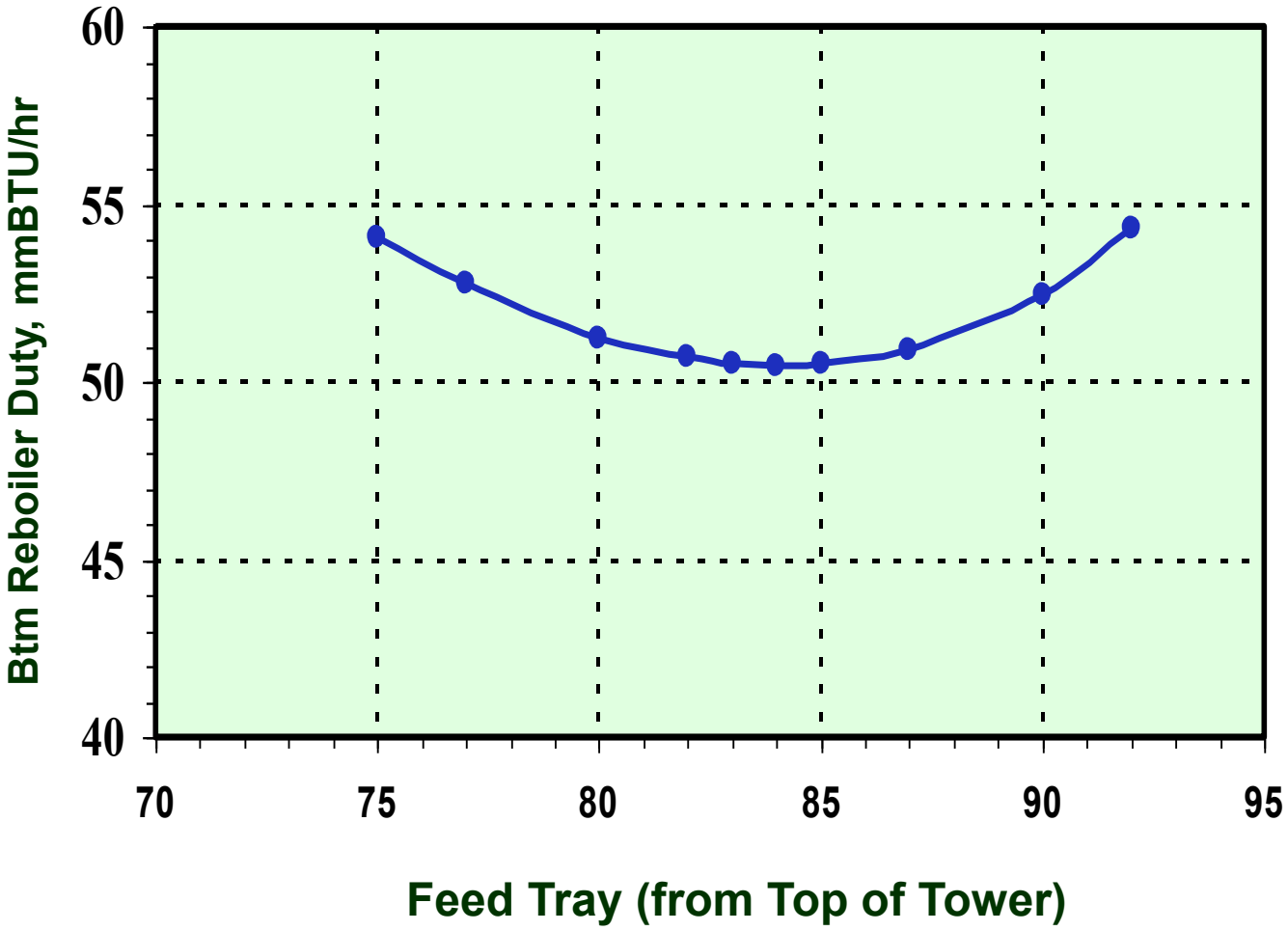
Can help you find the Optimum Feed Point.



Simulations also generate Theoretical Stages vs. Reflux Ratio Curves

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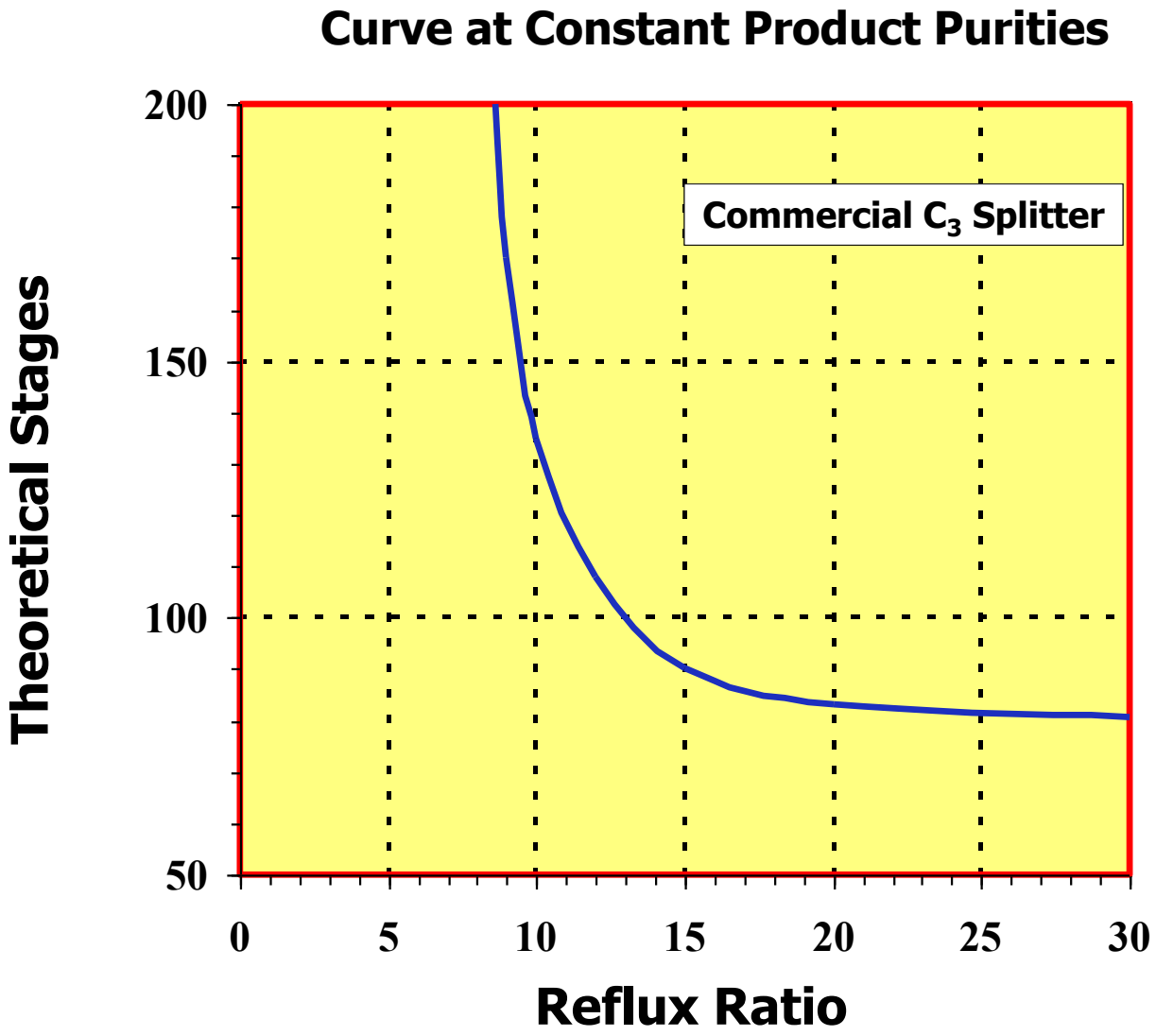

Optimum Design

An Optimum Design is one that minimizes Capital Investment while satisfying Operational Needs

Minimum Capital in a Distillation Tower is usually represented as least No. of Actual Trays or Packed Height

Good Operation dictates that a 10% shortfall in performance must be accommodated by a 10% maximum increase in Reflux Ratio.

Optimized Design

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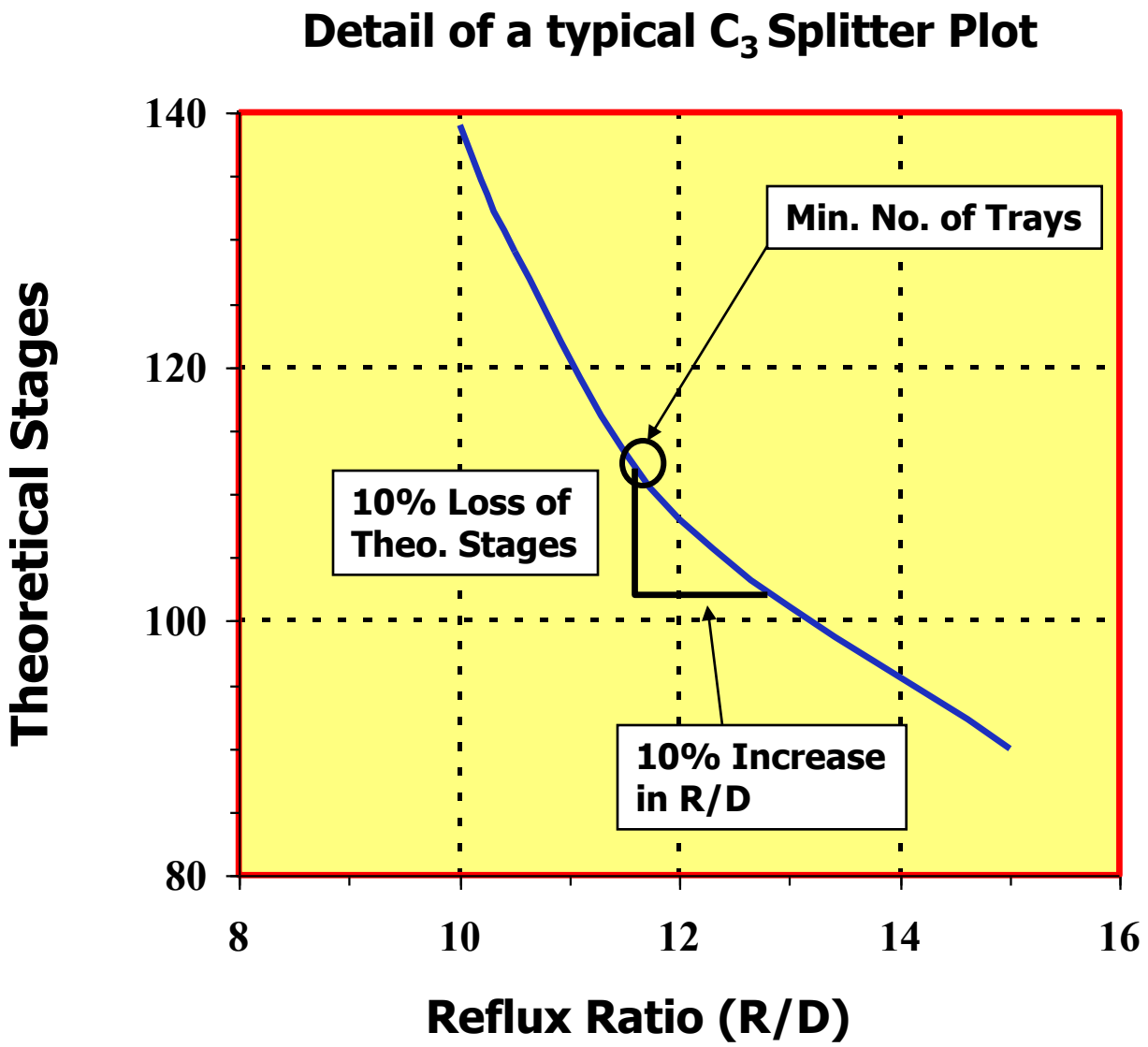


Design

Be careful with Computer Simulations. They are only as good as the data used to make them.

Superfractionators (i.e. C_2 , C_3 , & Xylene Splitters) simulations need to be checked against or fitted to available VLE data ! These towers have relative volatilities around 1.05 to 1.10 and small errors will result in a large effect on the number of Stages to use for design.

Watch out for Pinch Points and convergence problems!

The Whole Purpose

Once a Number of Theoretical Stages has been established, a Heat & Material Balance can be made for a given Feed and Product Rate.

The Heat & Material Balance Simulation allows the designer to determine the Internal Loads and Physical Properties needed for Design/Evaluation.

Towers

With the Internal Loads and Physical Properties one can size new towers or check the capacity of existing ones.

There are 2 general categories of internals for towers;

Trays and Packings

In the Packing category there is both Random Packing and Structured Packing.

Towers

How does one pick between Trays and Packings?

Rule #1) If pressure drop is important - use packing

Rule #2) If Liquid Load < 3 gpm/ft2, use structured packing

Rule #3) If Liquid Load > 20 gpm/ft2, use trays or random packing

Rule #4) All other options are determined with economics.

Packing

How does one pick the type Packing?

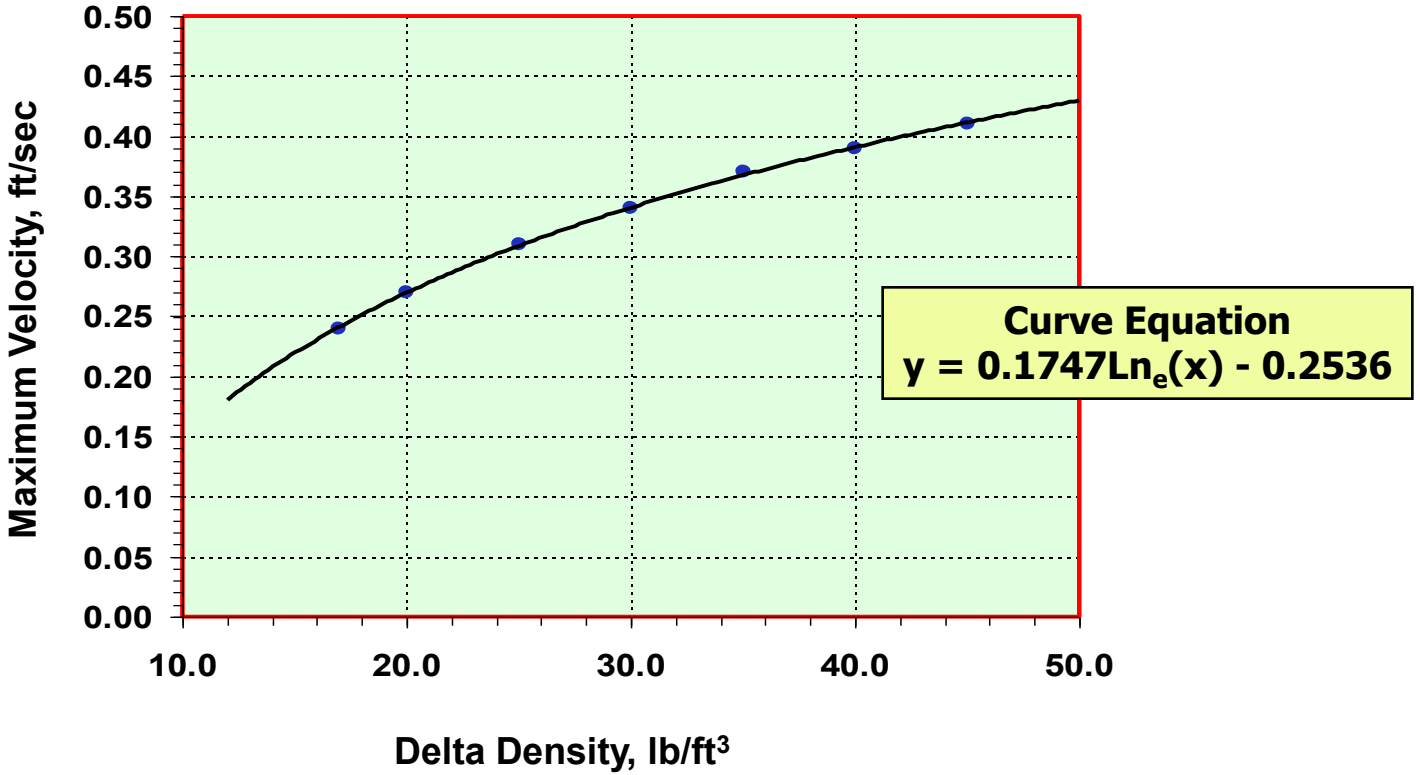
This is very simplistic, but basically use the highest surface area packing that does not flood. To prevent flood, keep the pressure drop per foot of bed height below 0.4 inches of water.

This will give you the lowest HETP (Height Equivalent to a Theoretical Plate) and the widest operating range.

Vendor software is very useful in calculating the pressure drop.

How does one determine a Tray design?

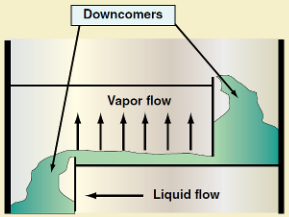
This is also very simplistic. Determine the downcomer area from the following chart. Then find the Active Area using the equations from June 2010 Chemical Engineering Magazine.



CHEMICAL ENGINEERING
FACTS AT YOUR FINGERTIPS
Department Editor: Scott Jenkins

Distillation Tray Design

In a distillation column tray, vapor passes upward through liquid that is flowing across a horizontal perforated plate. Vapor passing through the perforated plate forms a two-phase mixture with the liquid and enables mass transfer contacting. This mixture is typically quite turbulent. Tray design must allow the turbulent liquid to fall away from the rising vapor in the space above the tray, while also enabling the vapor bubbles to rise out of the falling liquid in the downcomer. The downcomer is usually a vertical plate that enables the already contacted froth to travel down to the next tray without remixing with the up-flowing vapor from the tray below.

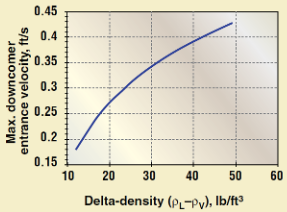


Side view of a simple tray arrangement

Generally, designing a column tray entails determining the minimum downcomer area that still allows vapor bubbles to rise through the liquid, selecting the number of downcomers, determining the active area, and checking the flow path length to see if a person can pass through a tray manway. These factors are the primary drivers for determining overall tower size.

Downcomer area is determined by the maximum recommended downcomer velocity. Divide the volumetric flow of liquid by the downcomer velocity to obtain the downcomer top area. Typically a curve of maximum downcomer velocity versus the density difference between liquid and vapor is consulted during this process.

Maximum downcomer velocity guideline



A downcomer is generally straight unless its area exceeds 8% of the tower area. In that case, the downcomer is sloped such that its bottom area is 60% of its top area.

Active area

The active area of a distillation tower is where the vapor contacts the liquid to effect mass transfer. Above the active area, where the liquid falls away from the rising vapor, is the volume where the vapor can expand. Typically, the active area is calculated to be the tower cross-sectional area minus the downcomer top and downcomer bottom area.

The minimum active area (ft^2) for normal valve trays can be determined from the following relationship, which is a modification of a commonly used correlation [1] taken at 82% of jet flood:

$$Active\ area = V\text{-}Load / [TS^{0.5} (0.0762 - 0.00092(\rho_V^2)) - 0.011W_L]$$

Where,
$V\text{-}Load = CFS_V (\rho_V / (\rho_L - \rho_V))^{0.5}$
TS = Tray spacing, in.
ρ_V = Vapor density, lb/ft^3
ρ_L = Liquid density, lb/ft^3
W_L = Weir loading, gal/min per in.
CFS_V = Vapor volumetric flow, ft^3/s

The required active area is dependant on the vapor density and weir loading. Note that the weir loading need not be known at this point. Assume a weir loading value of 5 gal/min per in. intially. Typical tray spacings are 24 in.

Tower area and diameter

Based on the above areas, the overall tower area and diameter can be determined by the following:

$$A_T = A_{Dtop} + A_{Dbottom} + A_A$$
$$D = 2(A_T/\pi)^{0.5}$$

Where,
A_T = Tower area, ft^2
A_{Dtop} = Downcomer area at top, ft^2
$A_{Dbottom}$ = Downcomer area at bottom, ft^2
A_A = Active Area, ft^2
D = Tower inner dia., ft

Number of downcomers

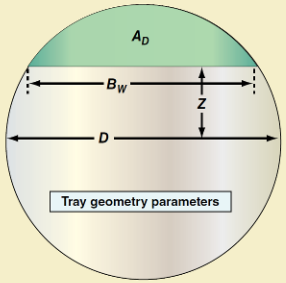
Once the tower diameter is determined, then the number of downcomers can be chosen. As a starting point, an initial design should use a single downcomer. The resulting weir length is calculated from a standard chord-length calculation, which is iterative for a given downcomer area.

$$B_W = \{[(\pi D^2/360)\ cos^{-1}(2Z/D)] - 2A_D\}/Z$$

Where,
$Z = [(D^2/4) - B_W^2]^{0.5}$
B_W = Weir length of one downcomer, ft

A good place to start the iterative process is with a weir length 0.8 times the tower diameter. If the resulting weir loading is greater than 12 gal/min per in., then increase the number of tray passes to two. Recalculate the outlet weir length for each of the side downcomers of the column by using half the downcomer area. Check the weir loading again (for the tray with side downcomers). If the weir loading continues to exceed 12 gal/min per in., increase the number of tray passes to four. It is assumed that the two-pass tray with side downcomers has the shortest weir length.

The simplest approach to designing 4-pass trays is to assume equal bubbling area and make the side downcomers one-quarter of the total downcomer area, and make the center (and off-center) downcomers one-half of the total downcomer area.



Maintaining the resulting downcomer widths at 6 in. or more will allow a person to reach into the downcomer for installation. In addition, make sure the resulting tray flow path length is 16 in. or greater to enable a person to physically pass through the trays. These minimum size criteria may increase the column diameter to above the previously calculated value.

Other considerations

Other criteria that need to be considered are; downcomer backup, spray fluidization, and entrainment. In addition, minimum load conditions need to be determined. The criteria for determining the low-end vapor and liquid range are weeping, tray stability and dry-tray pressure drop.

Reference

1. Glitsch Inc. "Ballast Tray Design Manual; Bulletin No. 4900." 3rd Ed. Glitsch Inc., Dallas, Tex.,1974.

Note: Material for the June "Facts at Your Fingertips" was supplied by Dan Summers, tray technology manager, Sulzer Chemtech USA Inc.

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Chemical Engineering Magazine June 2010

From AIChE Spring 2011 Paper 9e

$$DCVel = 0.1747 Ln_e(\rho - \rho \quad - 0.2536$$

$$A_D = \frac{Lload}{DCVel}$$

$$A_A = \frac{Vload}{FS^{0.5}(0.07616 - 0.00092\rho^2 \quad - 0.011W_L}$$

$$A_T = 1_{D_{TOP}} + 1_{D_{BOTTOM}} + 1_A$$

$$D = 2\left(\frac{A_T}{\pi}\right)^{.5}$$

Vendor Software

Vendor's public Software, such as Sulzer's SulCol3, is very useful to size and rate Tray and Packing designs.

SulCol version 3.0.8 has recently been upgraded to accommodate Vista and Windows 7 operating systems

SulCol 3 – Hydraulic Input

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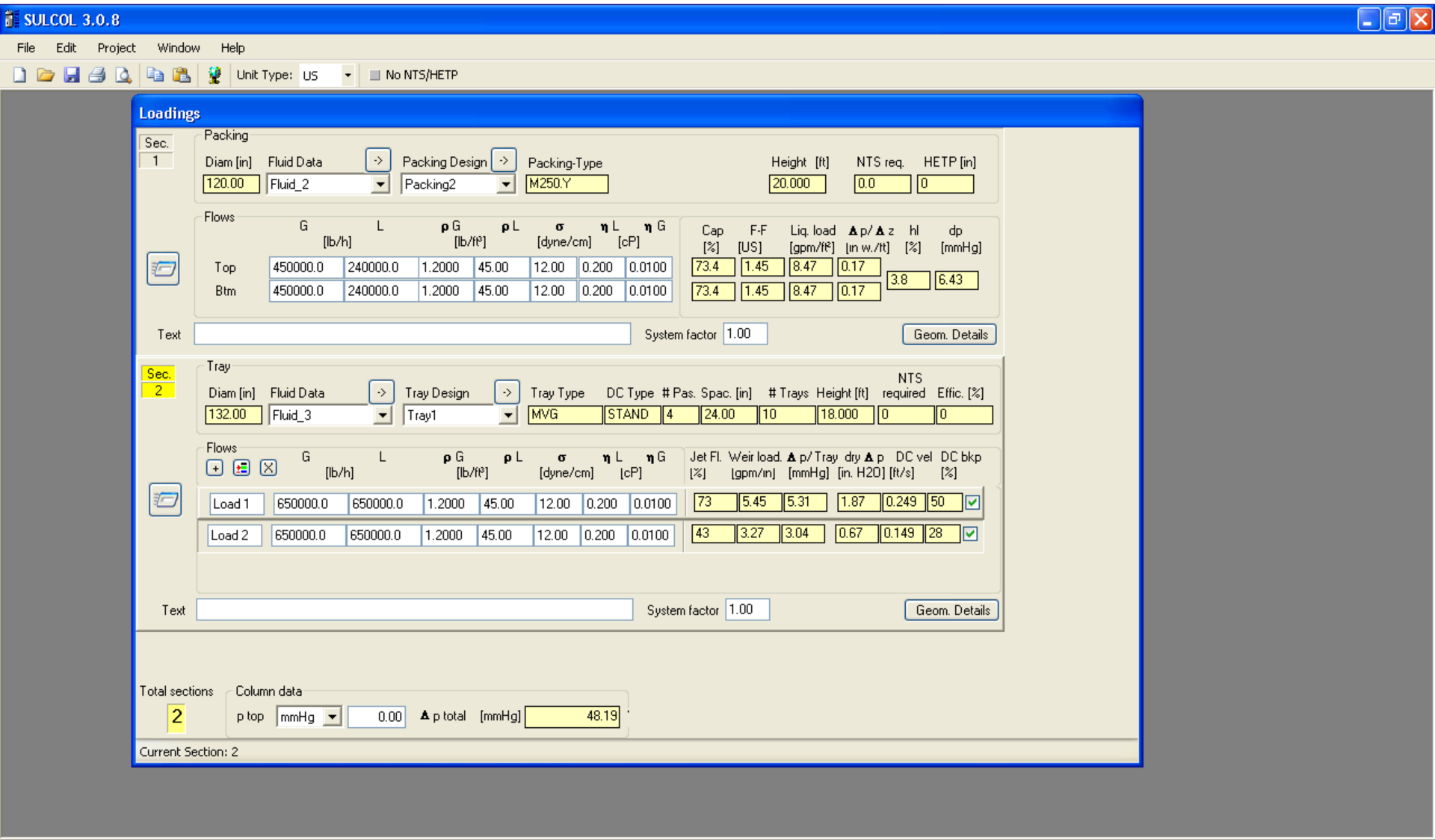

SulCol 3 – Tray Detailed Output

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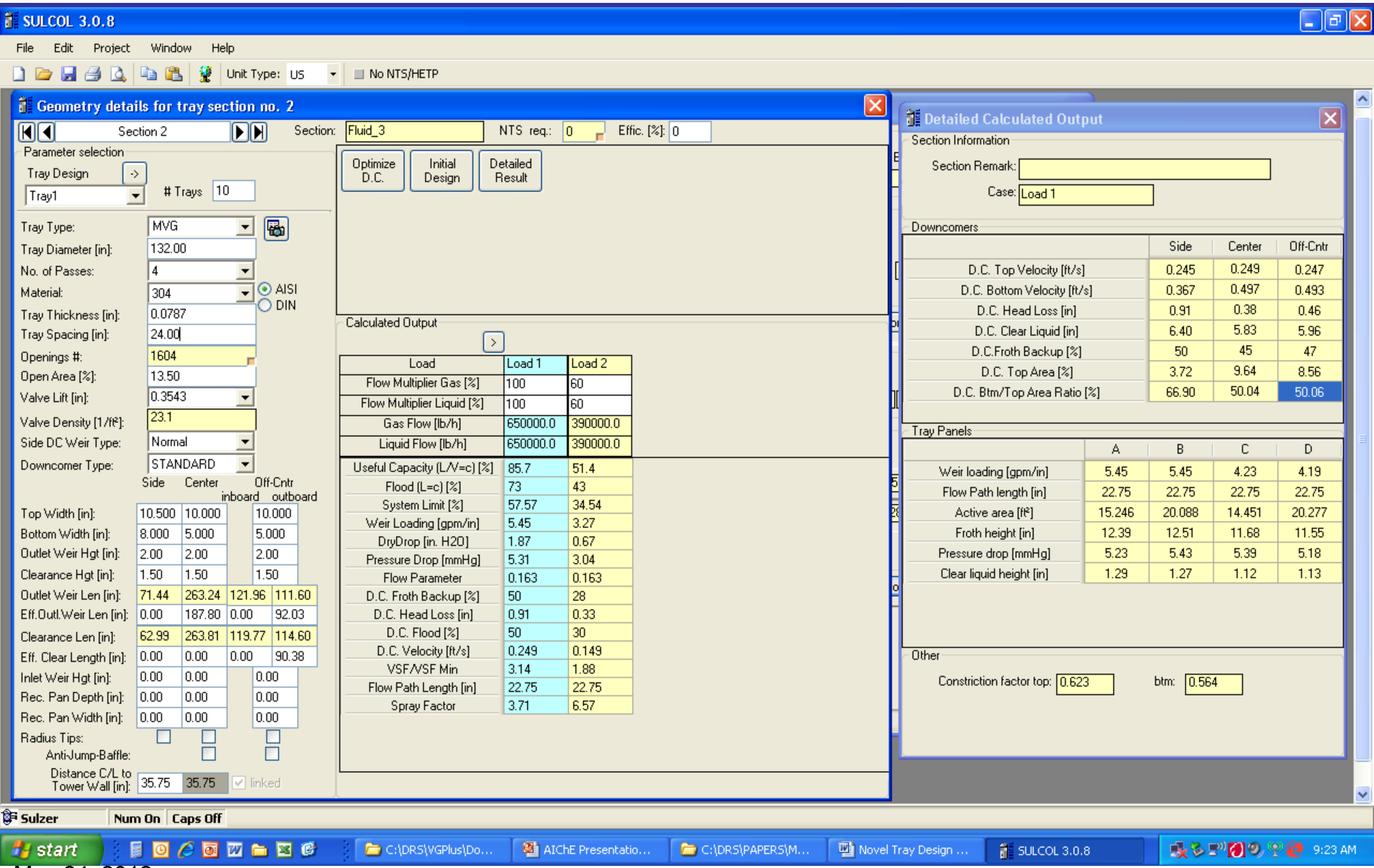

Packing Major Improvements

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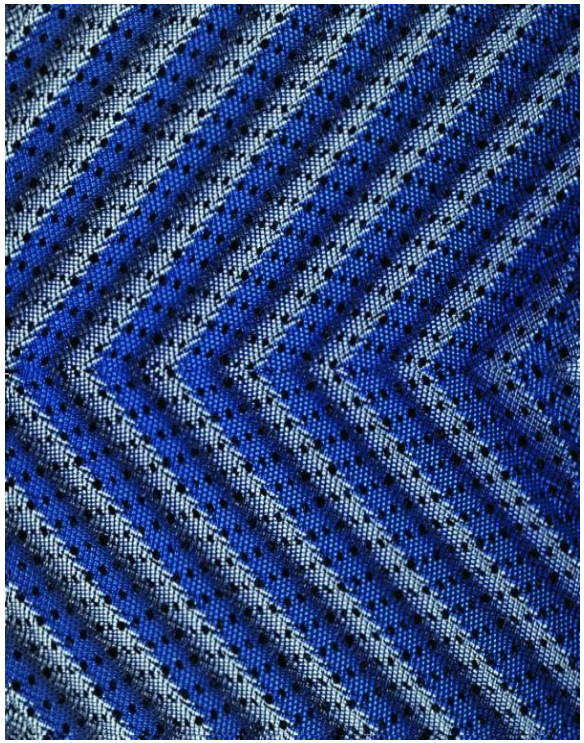

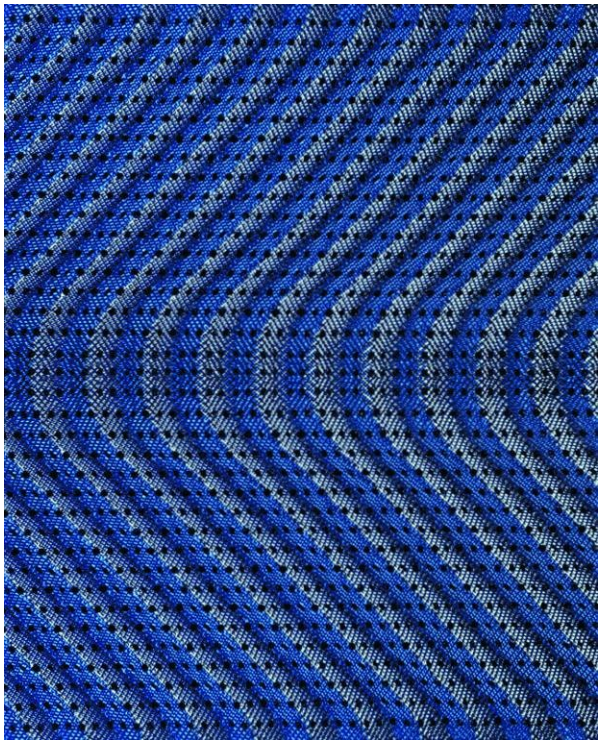

In the past 10 years, the industry recognized that packing capacity was limited at the interface between packing layers. Sulzer's solution was to 'bend" the packing at the top and bottom of the layer reduce liquid holdup at the interface.

M250.Y MellapakPlus in Crate

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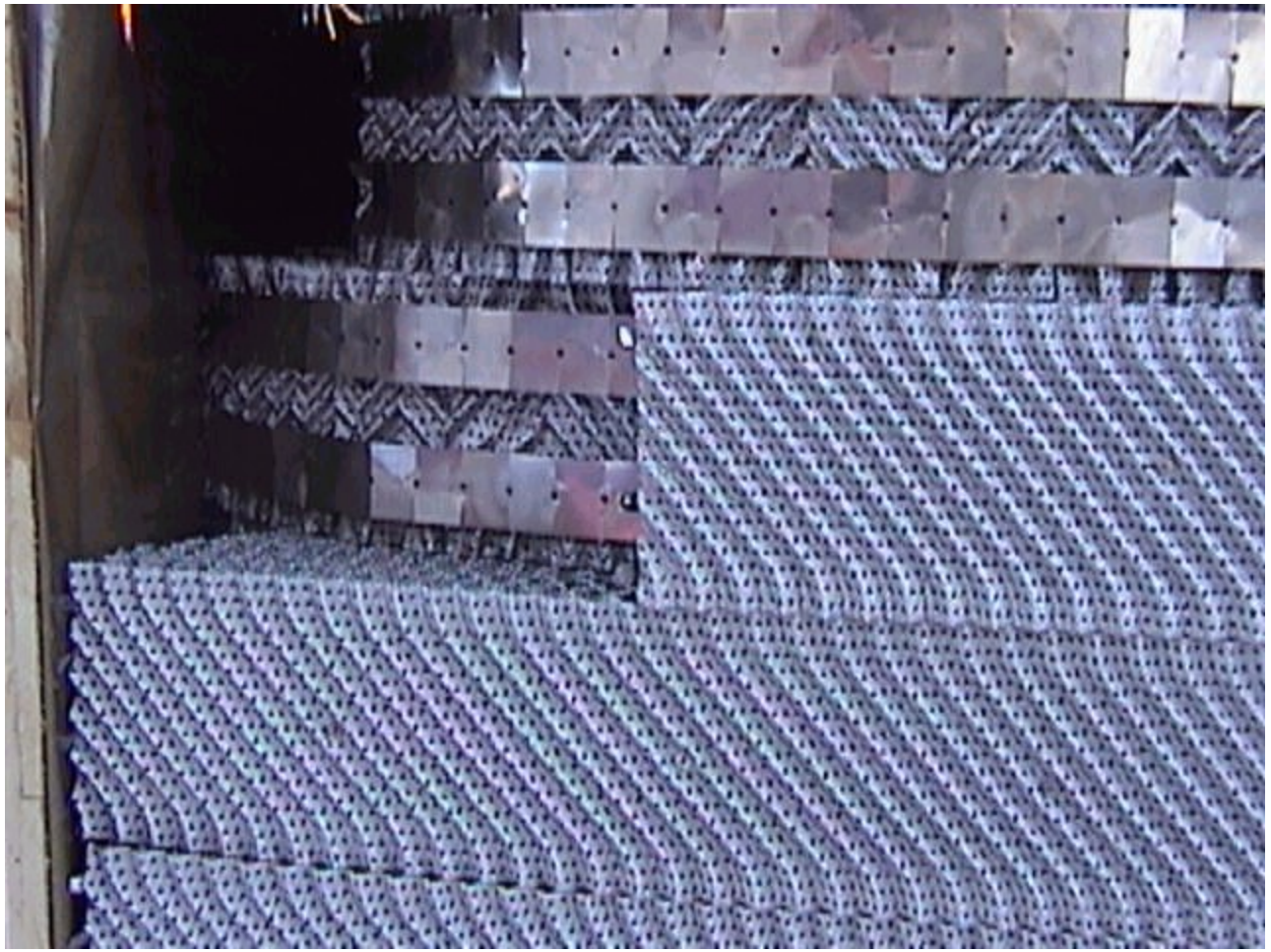

Packing Major Improvements

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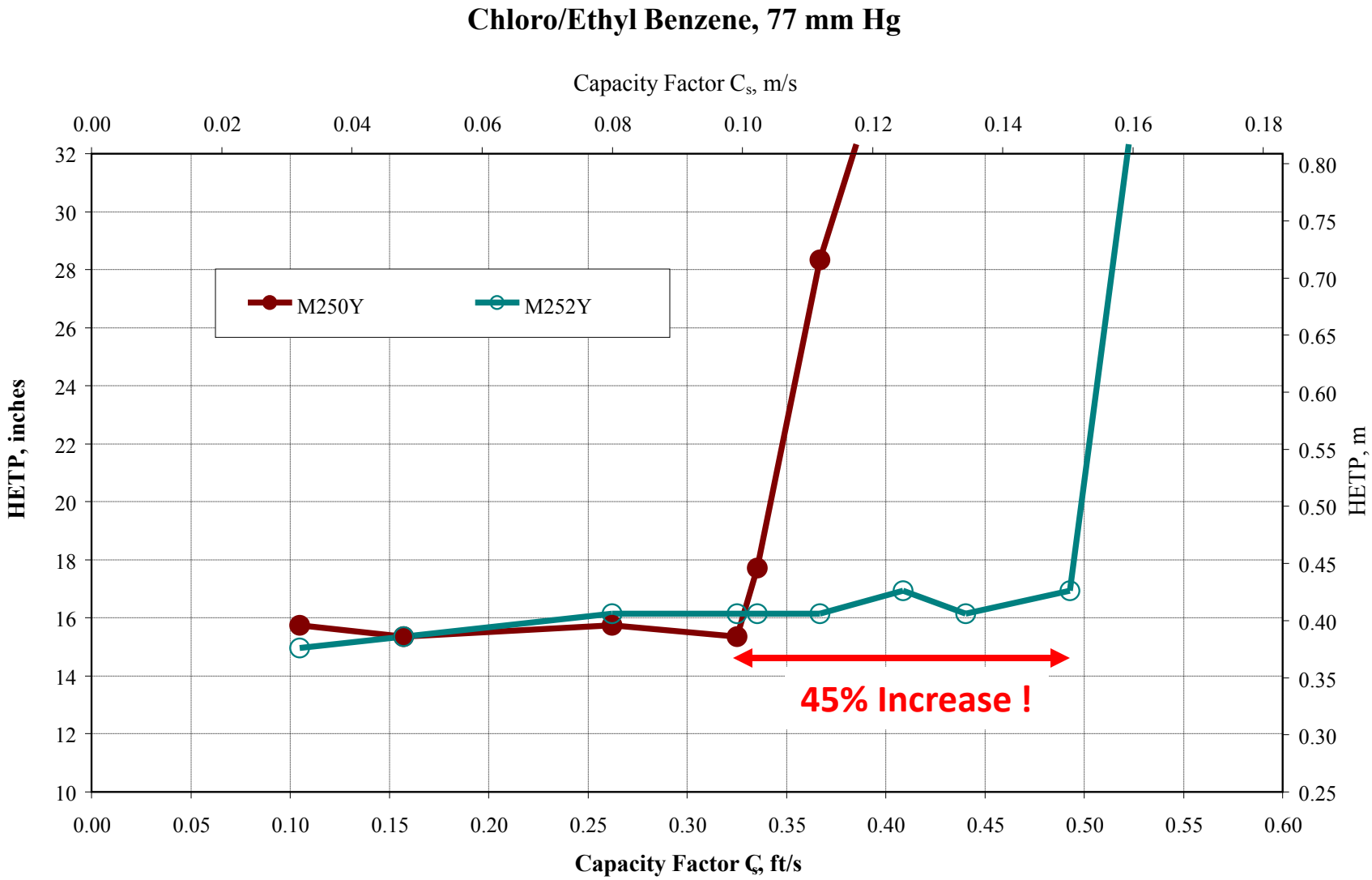

Tray Major Improvements

In the past 10 years, the industry realized that with high capacity trays utilizing truncated and highly sloped downcomers, smaller tray deck openings and tray deck enhancement features, that there is a maximum capacity "wall." This wall is called gravity.

Once every cubic inch of tower volume is utilized for liquid disengagement above a tray, then gravity will limit vapor capacity.

Other forces need to come into play to gain extra capacity in trayed distillation towers.

Tray Major Improvements

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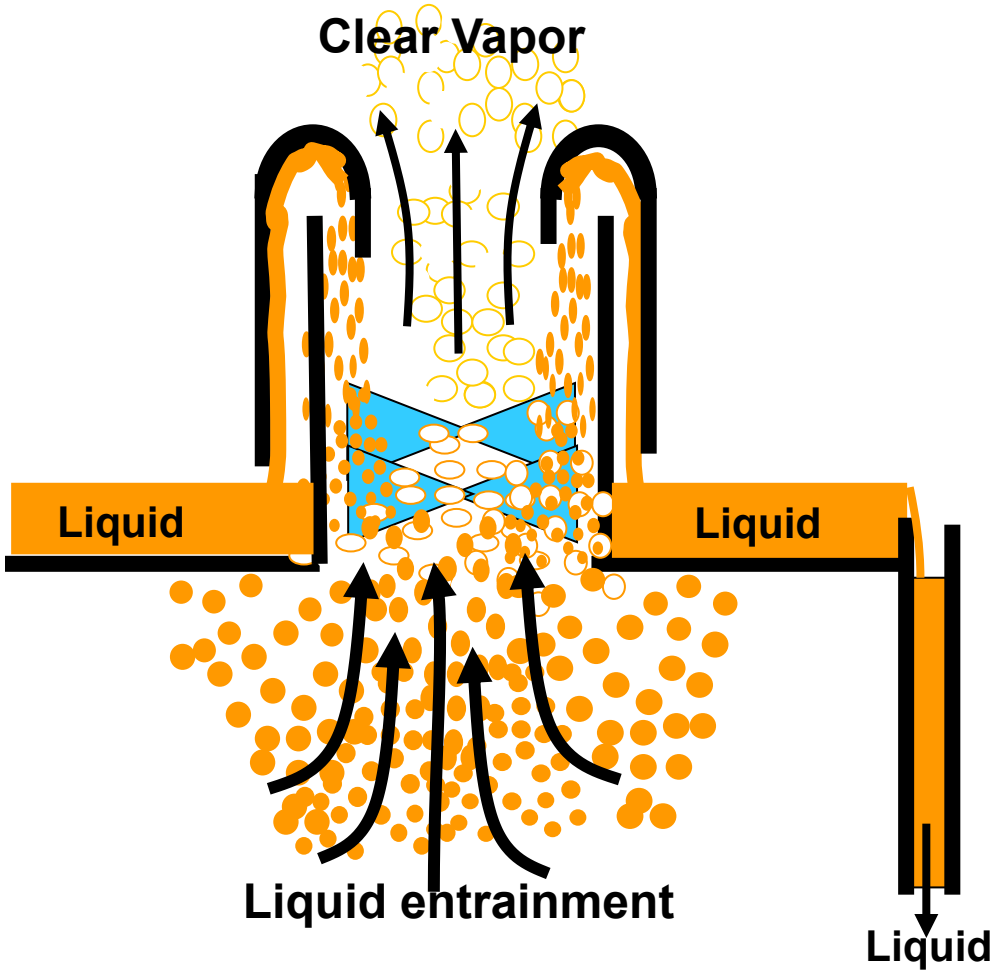

Shell's solution is to use operate a tray flooded and then use Centrifugal force to separate the entrained liquid from the vapor.

ConSep Tray

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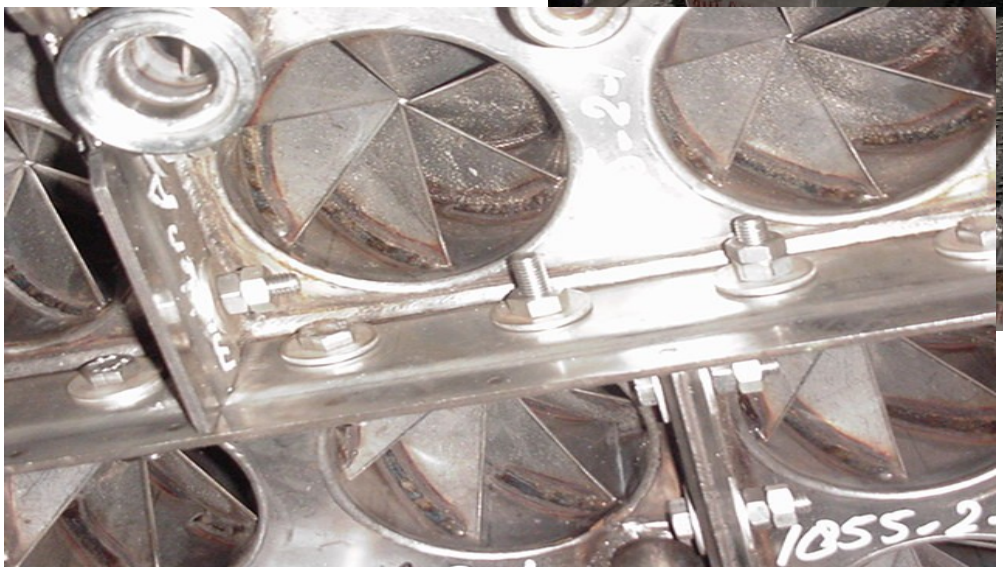

Tray Major Improvements

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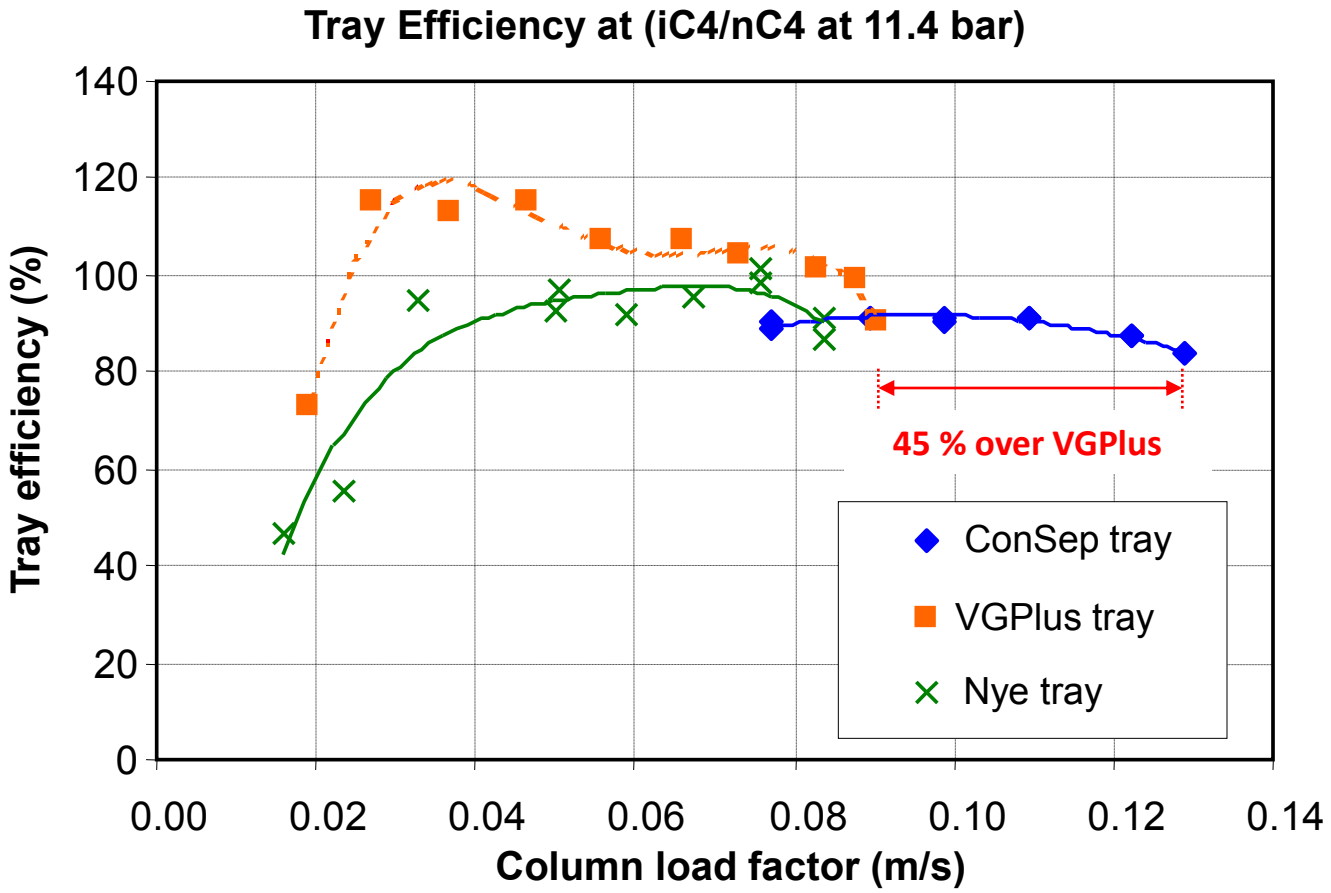

This is a substantial increase in Capacity over the best "gravity limited" technologies.

Packing Distributor Technology

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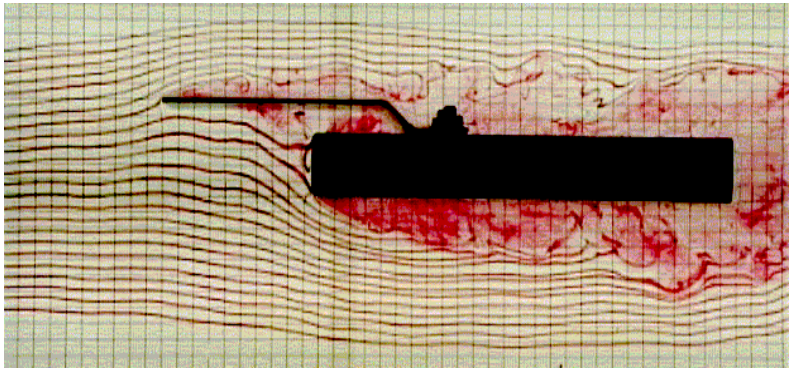
You can have the best packing in the world but this packing can only be as good as the initial distribution. A poor distributor will make the best packing operate poorly.

Pour point density, uniformity of distribution and available liquid head are a few of the important parameters that enable a good liquid distributor design.

Recent improvements in distributor design are lower pressure drop (of the vapor passing the distributor) and aerodynamic design.

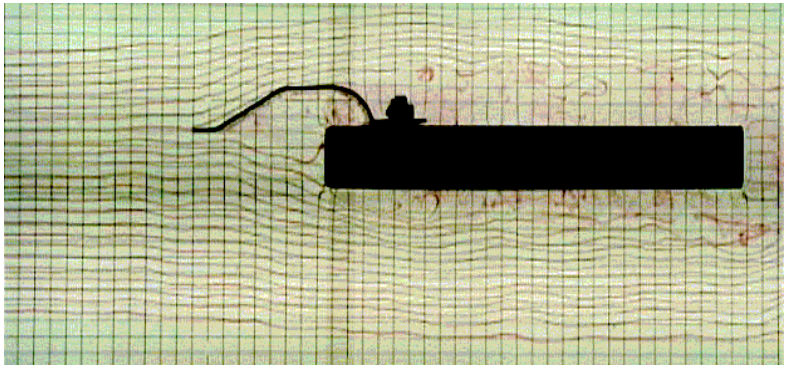
Splash Plate Distributor

Old VEP:



Former VEP

Current VEP:



New VEP

New BDH Tray

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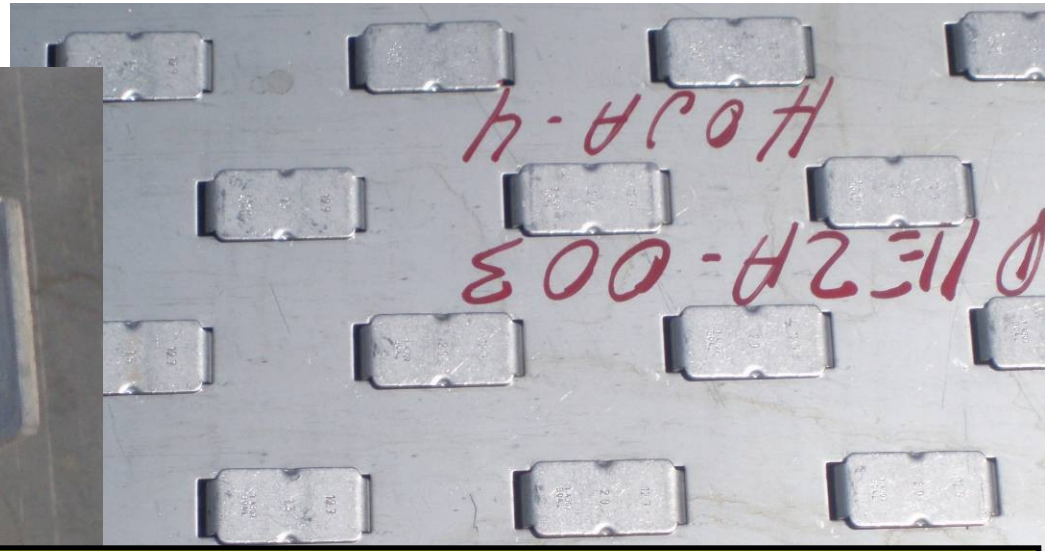

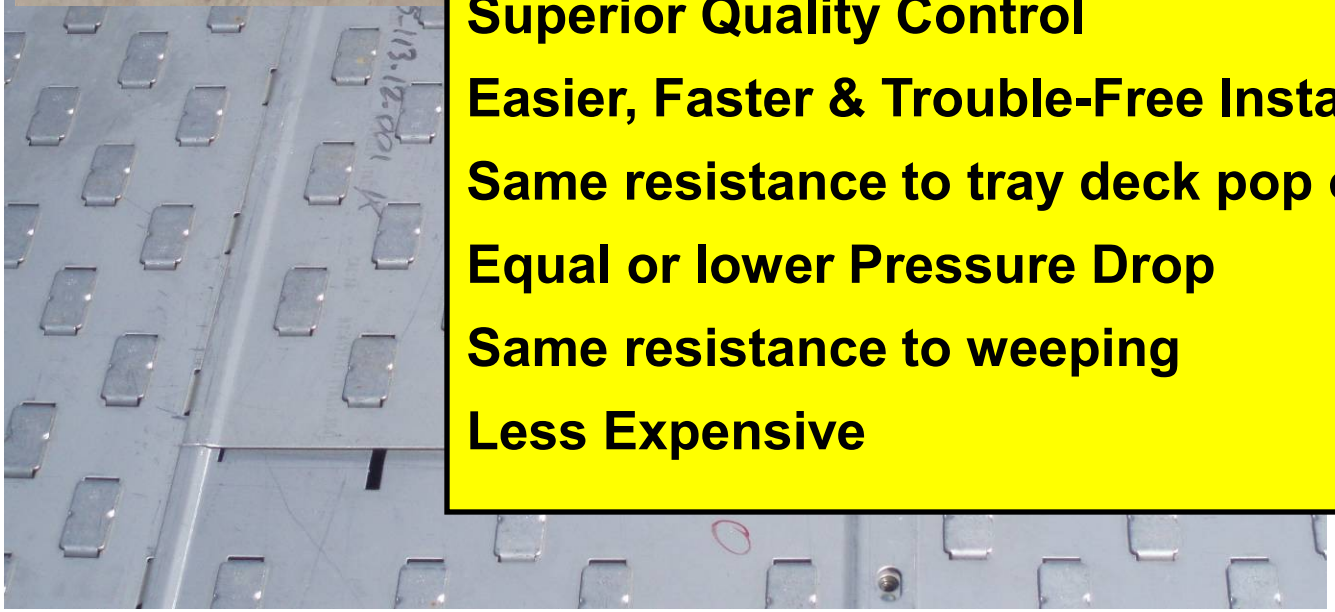

- **Superior Quality Control**
- **Easier, Faster & Trouble-Free Installation**
- **Same resistance to tray deck pop out**
- **Equal or lower Pressure Drop**
- **Same resistance to weeping**
- **Less Expensive**

Constant Improvement

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The existence of such companies as Sulzer Chemtech and our competitors such as Koch-Glitsch, Jaeger-Raschig, UOP, Montz and ACS-Amistco depends on the continuous improvement in distillation technology.

We all are trying to make a better "mouse-trap." It was stated more than 20 years ago that Distillation was a mature Science and that no major improvement would be achieved. Since that statement was made, all of the improvements discussed here within were invented and commercialized.

Constant Improvement

In addition, there is company solely dedicated to promoting continued research into distillation called FRI.

FRI (Fractionation Research Incorporated) is a non-profit research consortium supported by memberships which include many of the largest petroleum, chemical, and engineering companies in the world. It was founded in the 1950's to engage in research that was too expensive for any one company.

That research includes the only independent commercial scale distillation experimentation program operating with hydrocarbon systems at pressures ranging from deep vacuum to 500psia. The current membership of over 70 companies includes many leading companies in the field of distillation. Over 60% of the membership is international.

Concluding Remarks

At AIChE National meetings there are annually more than 75 papers presented on Distillation alone. In addition, there are regional meetings, such as the South Texas Region that, has another 6 papers presented (and has more attendance than the national meetings.)

Is this the sign of a mature discipline?

Distillation, as the world's "oldest profession," is far from being a mature science. As long as this unit operation is used as the work horse to provide the overwhelming majority of separations, it will continue to see improvements as the years and decades go by.