Packed Tower Internals Important to Tower Efficiency

By
Frank Rukovena, Jr. & Tony J. Cai
Fractionation Research, Inc.
424 S. Squires St
Stillwater, OK 74074

T8003
Paper 64a
Presented AIChE Spring Meeting
Distillation Symposium
April 28, 2009
Tampa, FL

Packed Tower Internals Important to Tower Efficiency

By
Frank Rukovena, Jr.[*] & Tony J. Cai
Fractionation Research, Inc.
424 S. Squires St
Stillwater, OK 74074

Abstract

The affect of liquid distributor design on apparent packing performance in distillation service at 24 psia with cyclohexane/n-heptane is demonstrated and related to the distributor design. The data presented was taken by $\text{FRI}_{(SM)}$ in its 48 inch diameter distillation tower with 1 inch metal Pall rings and in an 18 inch diameter column operated by Separation Research Project (SRP) located at the University of Texas at Austin. A pour point layout analysis of three of the four liquid distributors was performed by Amistco Separation Products with the WelChem program using the Moore/Rukovena method. The results demonstrate that the distributor pour point layout can be linked to apparent packing performance. These results along with previously published FRI data on how liquid distributor pour point density and flow variation patterns such as random and zonal affects the apparent packing efficiency. The data are used to support good liquid distributor design criteria presented in the paper.

Keywords: Distillation, Liquid Distributors, Packing Performance, Liquid Maldistribution, Pall Rings, Packed Beds

---

*Corresponding author. E-mail: rukovena@fri.org , Phone: 1-918-336-7140, Fax: 1-918-336-7014

Introduction

This paper will discuss how packed tower internals affect packed tower performance. The examples in this paper will include random packed towers only but what is said also applies to towers packed with structured packing. The paper has seven main sections:

- Background
- Examples of Liquid Distributor Design on Packing Performance
- Distributor Pour Point Layout Effect on Packing Performance
- Distributor Pour Point Density Effect on Packing Performance
- Random Distributor Liquid Maldistribution vs. Zonal Distributor Liquid Maldistribution
- Good Liquid Distributor Design Practice – Macro Scale

Items Affecting Uniform Liquid Orifice Flow – Micro Scale

Background

When designing a mass transfer tower using packing or trays to make a desired separation, the process engineer determines the required number of Theoretical Plates (TP) at a specific Liquid to Vapor (L/V) ratio. Only with the design L/V ratio and number of TP will the desired separation be achieved. The process designer determines the packing depth required by multiplying the TP by the expected Height Equivalent to a Theoretical Plate (HETP) of the packing being considered for use. Significant variation from the design L/V can cause an equilibrium pinch point in the under-irrigated areas of the packed bed preventing the separation from being achieved in that area of the tower. See Figure I – Impact of Varying L/V Ratio[1].

Upon startup when this poor performance happens, without realizing it, the process designer assumes that the design L/V ratio is being achieved in all parts of the packed tower and that the separation is not being achieved because the packing is not working. That is, the packing is not developing the number of TP required inferring a higher than expected HETP. When, in fact, even with the poor separation, the packing is contacting the vapor and liquid streams as it should. The poor separation is being caused by an improperly distributed liquid from a malfunctioning liquid distributor. The malfunctioning liquid distributor is causing pinching with varying L/V ratios in different parts of the tower and the tower is being evaluated with the design L/V ratio. When using the design L/V ratio to the do the evaluation, the only way to match the actual tower performance with a process simulation is to lower the TPs in the simulation. This makes the packing appear not to be working when the actual cause of the poor separation is the liquid distributor.

Examples of Liquid Distributor Design on Packing Performance

The following four examples demonstrate how a liquid distributor's design affects the distillation performance of 1inch metal Pall rings separating cyclohexane/n-heptane (C6/C7) at 24 psia.

Figure II - V-Notch Trough & FRI$_{(SM)}$ 48" TDP Liquid Distributor shows that the liquid distribution provided by the V-Notch trough liquid distributor resulted in the 1inch metal Pall rings producing an HETP of 24 inches and 15 inches respectively[2]. Both distributors were tested in FRI's 48 inch diameter tower with a 12 foot bed of 1inch metal Pall rings.

---

[1] Rukovena , F., Tony Cai, "Achieve Good Packed Tower Efficiency," Chemical Processing, p. 22-31, (November 2008)

[2] Kunesh, J.G., and A. Shariat, "Packing Efficiency Testing on a Commercial Scale with Good Reflux Distribution," Fig 13, AIChE Spring National Meeting, (March, 1993)

Figure III – $\text{FRI}_{(\text{SM})}$ Small TDP Distributor and Figure IV – Third Party Distributor[3] shows that the liquid distribution provided resulted in the 1inch metal Pall Rings producing HETPs of 19 inches and 18 inches respectively. Both distributors were tested in SRP's (Separation Research Project at the University of Texas at Austin) 16.9 inch diameter tower with an 8 foot bed of 1 inch metal Pall rings.

Distributor Pour Point Layout Effect on Packing Performance

It can be seen from the above discussion of Figures II, III, & IV that all four of these liquid distributors with different designs resulted in different HETPs. The following discussion relates the pour point layout analysis for three of the four distributors to the packing performance in the packed bed under that liquid distributor. The pour point analysis method used was the empirical method proposed by Moore & Rukovena[4]. Additional details about this method will be given below in the analysis of FRI's 48 inch TDP distributor.

Figure V – $\text{FRI}_{(\text{SM})}$ Tube Drip Pan Distributor is a picture of the large FRI TDP liquid distributor.

Figure VI – $\text{FRI}_{(\text{SM})}$ TDP Distributor Layout is the pour point layout of the large FRI TDP liquid distributor.

Figure VII – Distribution Pattern Quality, 91.1% is the visual representation of pattern analysis of Moore & Rukovena. This analysis divides the superficial tower cross-sectional area by the number of pour points in the distributor. The diameter of a circle with this area is located at the point on the top of the packed bed directly beneath the orifice location in the distributor layout. The method assumes that the liquid distributor is centered in the tower and that the liquid leaving the pour point enters the packed bed directly below the pour point. The method then looks for the one- twelfth area that has the greatest deviation from the average flow per unit area and determines a distribution quality percentage. This quality number is then related to packing performance. The lower the quality number, the lower the packing performance will be from its expected performance with a 90+% quality number distributor. The underlying concept of this method is that the packing is always contacting the vapor and liquid per its mixing capability and that the separation will be achieved only if the L/V ratio of the design is achieved without equilibrium pinching. This, of course, assumes that the design HETP was properly predicted, or measured, with a good liquid distributor. The method can be

---

[3] Data via private communication from Dr. Frank S. Siebert of SRP at the University of Texas at Austin, TX

[4] Moore, F., F. Rukovena, "Liquid and Gas Distribution in Commercial Packed Towers," CPP edition Europe, p. 11 (August 1987)

used to predict the decline in efficiency with declining distributor layout quality. In this paper, the quality number will just be compared to the measured HETP generated with that distributor to demonstrate that the distributor design is important to obtain good packing performance. With the 91.1% pattern quality FRI TDP liquid distributor, the HETP was determined to be 15 inches.

Figure VIII – FRI$_{(SM)}$ Small TDP Distributor is a picture of the small FRI TDP liquid distributor with 16 pour points.

Figure IX – Distributor Pattern Quality, 73% - Small FRI$_{(SM)}$ TDP is the graphical representation of pour point pattern analysis of this distributor. The HETP for this distributor was determined to be 19 inches.

Figure X – Third Party Distributor and Figure XI – Distributor Pattern Quality, 72.6% are a picture and the pour point pattern graphical analysis of this third party liquid distributor respectively. With the 72.6 % pattern quality, the HETP was determined to be 18 inches.

Table I – Distributor/Packing Performance gives the comparison of the pattern quality numbers to the HETPs generated by the packing for the two FRI TDP distributors and the Third Party distributor. The distributors with the nearly equal and lowest pattern quality numbers of 72.6% and 73% had essentially equal HETPs of 18 inches and 19 inches respectively, a 5.6% difference. Both of their HETPs are significantly higher than the 15 inch HETP achieved with the 91.1% pattern quality liquid distributor. Based on the average HETP achieved, the two small distributors had an HETP 23.5% greater than the 91.1% pattern quality distributor. A pattern analysis of the V-Notch trough distributor was not determined because the dimensions of the distributor were not available so the author (F. Rukovena) “guesstimated” the 30% quality number based upon his experience.

The HETP value was selected per the method illustrated in Figure XII - HETP vs. Maximum Useful Capacity Definition. This method takes the horizontal portion of the performance curve as the typical HETP. The highest capacity at which the HETP still equals the typical HETP is the maximum useful capacity[5]. This definition of useful capacity is also used on Figure XIV.

Distributor Pour Point Density Effect on Packing Performance

Figure XIII – Pour Point Density Effect on Theoretical Stages indicates that there is only minor improvement in packing performance with liquid distributor pour point densities

---

[5] Strigle Jr., F.R. and Rukovena Jr., F., “Design of Packed Distillation Columns,” Chemical Engineering Progress, p. 86-91 (March 1979)

above four to five points per square foot[6]. The information on Figure XIII is further confirmed by the work reported in this paper (See Table I).

Random Distributor Liquid Maldistribution vs. Zonal Distributor Liquid Maldistribution

Figure XIV - Random Distributor Liquid Maldistribution Effects vs. Zonal Distribution Liquid Maldistribution Effects. Studies performed by FRI indicate that a ±12.5% random liquid maldistribution leaving the distributor and entering the top of the packed bed does not cause the packing performance to deteriorate but when that same level of maldistribution is located in one zone of the tower superficial area, the packing performance declined about 20%[7,8].

Good Liquid Distributor Design Practice – Macro Scale

A good liquid distributor design has the following attributes.

- A pour point layout that distributes the liquid evenly across the tower cross-sectional area

It can be seen from the data presented in Figures II, III, & IV HETP vs. capacity curves and the pour point layout analysis presented on Figures VII, IX, and XI that it is essential that liquid pour points distribute the liquid evenly across the top of the packed bed.

- Adequate number of liquid pour points

The information presented indicates that once the pour point density is above five per square foot, increasing the pour point density does not greatly increase the packing's performance.

- Uniform liquid flow from pour points

The zonal maldistribution vs. random maldistribution data presented on Figure XIV indicates that a packing's performance is not seriously degraded with a ±12.5% random variation in liquid flow from pour point to pour point. But if the increased flow is in one zone of the tower and the decreased flow is in another zone of the tower as the liquid enters the top of a packed bed, the efficiency will be significantly reduced. This level of zonal maldistribution can be created in a number of ways. The distributor can be out of level, which increases the liquid head on one side of the distributor vs. the other. Or the

---

[6] Fitz C.W., D.W. King, and J.G. Kunesh, "Controlled Liquid Maldistribution Studies on Structured Packing," Presented at Fall National Meeting (Dallas), American Institute of Chemical Engineers, New York (Nov. 1999)

[7] Kunesh, J.G., L. Lahm, and T. Yanagi, "Commercial Scale Experiments That Provide Insight on Packed Tower Distributors," I&EC Research, Vol. 26, p. 1,845-1,850 (1987)

[8] Kunesh, J.G., "Recent Developments in Packed Columns," The Canadian Journal of Chemical Engineering, Vol. 65, p. 907-913, (December 1987)

distributor in a large tower can sag in the center of the tower causing greater head in the center of the tower than at the perimeter. The liquid leaving the feed pipe can cause a zonal maldistribution effect with high velocity head down the liquid troughs.

- Adequate vapor passage area

Although no data was presented on this subject, it is the author's experience that the vapor passage area of a typical distributor is between 30% and 50% of the tower area with the 30% being the more usual number. With a 30% open area liquid distributor and when the packing is operated at only one third of its capacity, the vapor velocity entering the vapor riser area is at a velocity sufficient to entrain liquid droplets back up the vapor risers. When the entrained droplets exit the vapor riser, they may fall back into the distributor and increase the liquid flow through the distributor causing it to flood prematurely. This is especially true when this occurs at a redistributor with vapor riser covers. At higher vapor velocities, the liquid droplets will enter the packing or trays above and lower separation efficiency by back-mixing effects and/or cause flooding of the device above the distributor

- Prevents, not promotes, liquid entrainment

The liquid leaving a distributor should not discharge into the vapor stream entering the vapor riser or into the vapor riser. As mentioned above, this will lead to liquid entrainment. And, even if liquid entrainment does not develop, the rising vapor can deflect the liquid leaving the pour point so it does not enter the packing at the desired location which can upset the packing performance. The positive solution to ensuring that the liquid leaving the distributor does not entrain or become mis-directed is to keep it shielded from the vapor stream with guide tubes or plates.

- Easy to level

Because the levelness of the distributor is important to good distribution, how the levelness of the distributor is to be obtained should be considered during the distributor design stage. How this is accomplished differs depending upon the type of distributor being designed. It is possible to hang some distributors with threaded rods so they can be leveled by adjusting the rod length. It is also possible to set some distributor types on support clips or ledges. In this case it is critical during the construction phase of the tower to make sure the support ledges or clips are properly installed. Leveling jack bolts can also be installed on the perimeter of the liquid distributor so it can be leveled once it is assembled in the tower on the support clips or ledge. In towers with a possible high upsurge potential, it is also a good practice to secure the distributor to the ledge or clip once it is leveled.

- Resists fouling

Although main examples discussed in this paper have orifices in the bottom of the pan deck, there are a number of good reasons to put the discharge orifices in the sidewall of the distributor. One of the main reasons is to prevent any start up dirt from plugging the orifices. Setting the orifices one to two inches up the trough sidewall provides a collection sump for dirt to settle into without plugging the orifice pour point. It is good practice to use as large an orifice as possible to make the distributor as fouling resistance as possible. A fouled distributor will cause packing performance to deteriorate so if fouling is a concern, a few large orifices will most likely be better than many small plugged orifices.

Items Affecting Uniform Liquid Orifice Flow – Micro Scale

- Orifice shape

Most liquid distributors use round orifices but many others use V or rectangular shaped orifices. Only the relationship between the liquid head for flow through a round orifice will be discussed but similar relationships apply to V shaped and rectangular orifices.

- Orifice flow equation[9]

$$Q_o=19.636Kd^2(h_o)^{0.5}$$

Where:

Q_o = Single orifice flow, gpm
d = Orifice dia, in.
h_o = Head on orifice, ft of liquid w/o vapor side head loss
K = Orifice discharge coefficient

(For Reynolds No's. between 200 to 10,000, K = 0.707[10] *which is a typical value for punched orifices with the liquid flowing in the direction in which the orifice was punched.)*

The important thing to take away from this relationship is functionality between the flow through the orifice and the liquid head on the orifice. It will be demonstrated in the section below discussing minimum head, where a small change in head can cause the flow rate leaving the distributor to exceed acceptable flow variation required for good packing performance, i.e. make the desired separation.

- Orifice edge shape
  - Use punched orifices when possible.

The edge shape of the orifice affects the orifice discharge coefficient. Use punched orifices when possible. Drilled orifices are not round and the drill makes a ragged edge. If it is necessary to use drilled orifices, remove the burrs.

  - Liquid flow should be in the punched direction.

The liquid flow should be in the direction of the punching because the punch cuts a sharp edged when entering and then produces a torn shaped edge as it exits the metal sheet.

  - For large distributors with high orifice count, maintain good QC on orifice size during punching

---

[9] "Cameron Hydraulic Data," C.C. Heald, ed., p. 67, Ingersoll-Rand Co. Montvale, N.J. (1994)

[10] Kister, H.Z., "Distillation Operation," p. 57, McGraw-Hill, New York (1989)

During large production runs, the punching tool dulls and the size of the orifice changes. If good QC practices are not in place, the orifice sizes will be different in a zonal manner, which is detrimental to packing performance as discussed above.

- Velocity of the liquid through the orifice.

The velocity of the liquid flowing through the orifice affects the orifice discharge coefficient. The coefficient can vary between 0.61 and 0.98[9, 10&11]. For punched orifices with Reynolds Nos. between 200 and 10,000, Kister[10] recommends using K=0.707.

- Liquid pool depth (head) above the orifice.

The total liquid pool depth above the orifice is a sum of the head to cause the fluid to flow through the orifice at the desired flow rate and the head to overcome the pressure drop of the vapor flowing through the vapor riser space. This can be expressed as follows:

$$h_{OA} = h_O + h_{PD}$$

Where:

h_{OA} = Total liquid head above Orifice, in
h_O = Orifice head, in
h_{PD} = Vapor side head loss, in

The maximum head (h_{OA}) is necessary to know for setting the height of the vapor risers and pan and trough arm sides in order to prevent liquid from entering the vapor riser or overflowing at maximum capacity operation. If liquid enters the top of the vapor riser, massive liquid entrainment and flooding will occur. It is common practice to make the vapor riser two inches higher than the total liquid head. The purpose of the freeboard is to allow for wave action and for orifice discharge coefficient differences between the design value and the actual value.

At minimum head, another issue needs addressed. It is the variation of orifice flow caused by wave action, unlevelness and/or horizontal velocity in the liquid pool above the orifice. If the allowable orifice to orifice flow variation is set as 12.5% with a ±0.25 inch head variation, the minimum acceptable pool depth is 2 inches[1]. If the head is decreased to 1 inch with a ±0.25 inch head variation, the total flow variation increases to 25.2%.

<u>2in Design head</u>[Ref1]

$$+6.1\% + \left| -6.5\% \right| = 12.6\%$$

<u>1in Design head</u>

$$+11.8\% + \left| -13.4\% \right| = 25.2\%$$

---

[11] "Perry's Chemical Engineer's Handbook," 6th ed., Robert H. Perry, Don W. Green and James o. Maloney, eds., p. 5-15 McGraw-Hill, New York (1973)

- Horizontal Liquid velocity across the orifice

Keep the horizontal liquid velocity low to prevent varying orifice discharge flow by the Bernoulli velocity affect.

- High velocity above the orifice reduces the head on the orifice decreasing discharge flow
- When the horizontal velocity stops at the distributor perimeter, the head increases, increasing discharge flow.
- Velocity head equation[12] is

$$h_V = 0.187\,(V_h)^2$$

Where:

h_V= Velocity head, in
V_h= Liquid velocity, ft/s

- At minimum head it is good practice to keep V_h below 1.25 ft/s

- Liquid feed pipe effects

The feed/reflux pipe liquid discharge can affect distributor pour point discharge. It should not discharge on an orifice or cause liquid waves especially at low head. So not to cause the flow variations by the mechanisms discussed above, it is suggested that the feed pipe discharge velocity be between 5 ft/s and 10ft/s[13,14]. At the higher velocity, consider using a momentum breaker. A momentum breaker can be a basket of packing beneath the discharge point.

- Fouling resistance

A plugged distributor is useless. Don't overlook the potential of start-up crud to ruin what would otherwise be a perfect startup. Any material left in the tower that can be introduced upon startup has the potential to plug the liquid distributors. To help prevent this problem:

Clean tower & distributors before start-up
Use as large an orifice size as possible
Use sidewall orifices to provide crud collection space below the orifices
If possible install permanent external piping strainers, if not use start-up strainers or screens
Clean piping between strainers and the distributors

- Redistributors

The concerns and criteria are the same as those for a distributor. The only additional considerations are:

---

[12] Kister, H.Z., "Distillation Operation," p. 63, McGraw-Hill, New York (1989)

[13] Kister, H.Z., "Distillation Operation," p. 31, McGraw-Hill, New York (1989)

[14] "Perry's Chemical Engineer's Handbook," 6th ed., Robert H. Perry, Don W. Green and James O. Maloney, eds., p. 5-48 McGraw-Hill, New York (1973)

Vapor riser covers that protect the collected liquid from the vapor stream are needed to prevent liquid entrainment.

Mixing of feed stream with the liquid at the feed point should be considered, if it is significantly different in composition from the liquid at the feed point.

Liquid cross mixing in redistributors between beds especially in large towers should be considered. One directional mix can be achieved by using vapor riser covers that discharge into a common area. For total cross mixing, a collector is needed above the redistributor.

Summary of Good Liquid Distributor Design

- Orifice flow variation random, ± 5% to 6%
- Head at minimum capacity, 2 inches
- Gas risers have a 2 inch freeboard above max pool depth
- Quiet liquid pool
- Low horizontal liquid velocity, <1.25ft/s
- Feed pipe discharge does not disrupt orifice flow
- Orifice as large as possible
- Use sidewall orifices if fouling is a concern with conductor tubes or spreader plate to guide liquid to top of packed bed & prevent liquid entrainment

Conclusions

Packed tower performance is dependent on the packing selected and the design of the liquid distributor being used. It is essential to pay close attention to the details of the liquid distributor/redistributor design to obtain good packed tower performance. The best way to ensure that these details have been addressed is to work closely with the engineering company and equipment supplier during the design stage well before the equipment is built and installed. Also, take care to make sure that construction debris is cleaned from the tower and associated piping before startup.

Acknowledgments

I would like to thank Dr. Frank Seibert of the Separation Research Project at the University of Texas at Austin for providing the Third Party Pall ring data and figure.
I would also like to thank Mr. Joshi Samuel of Amistco Separation Products in Alvin, Texas for providing the liquid distributor pour point analysis.

Figure I
Impact of Varying L/V Ratio
McCabe-Thiele Diagram

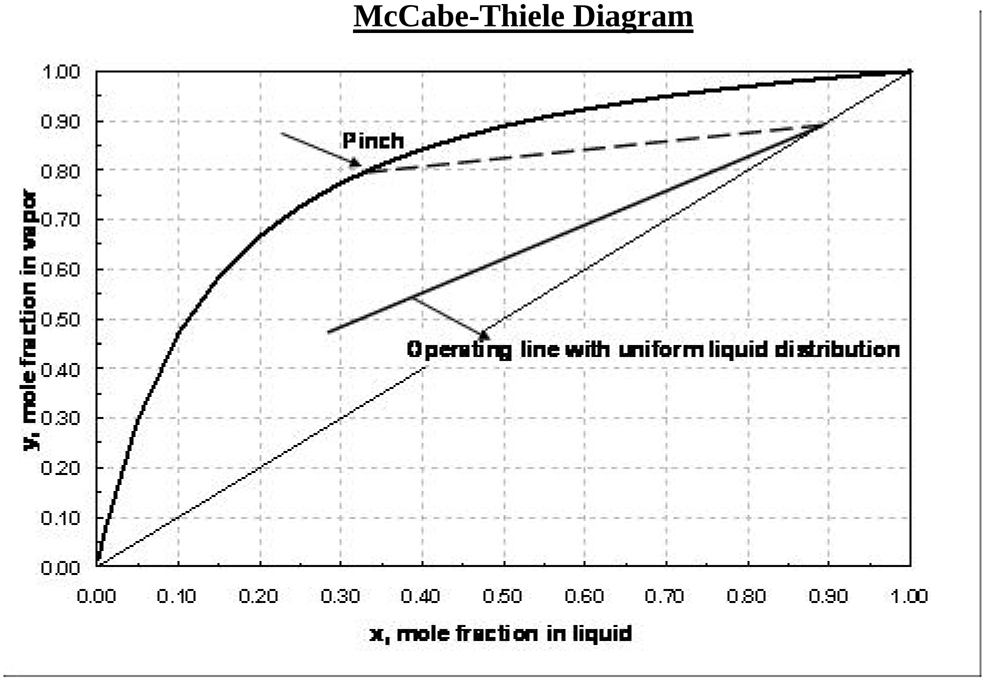


Figure II

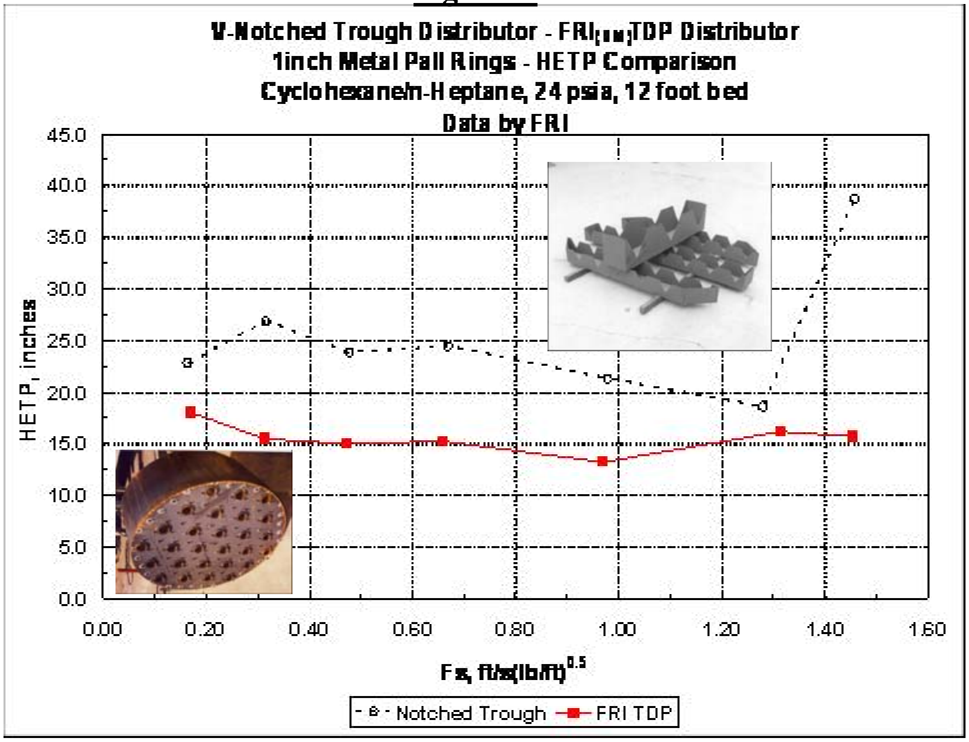


Figure III

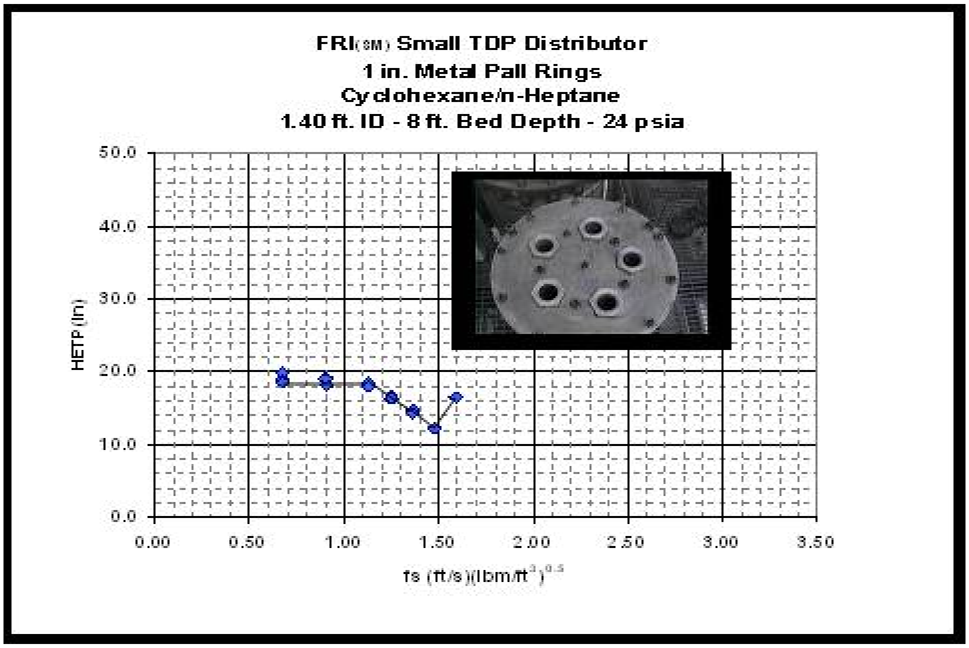


Figure IV

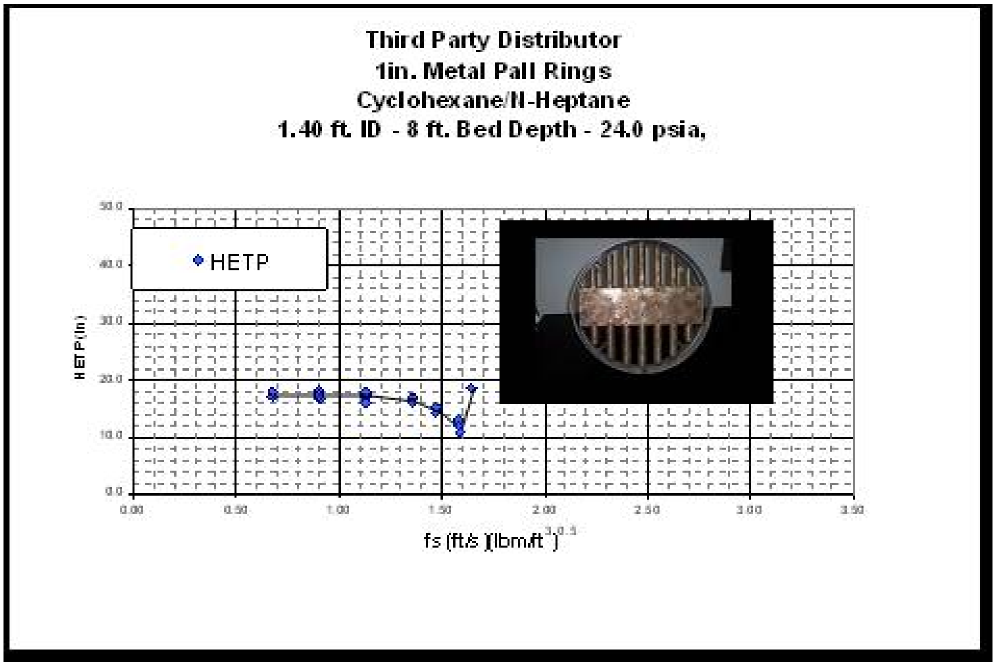


Figure V
FRI$_{(SM)}$ Tube Drip Pan Distributor
121 Pour Points, 48” id Tower

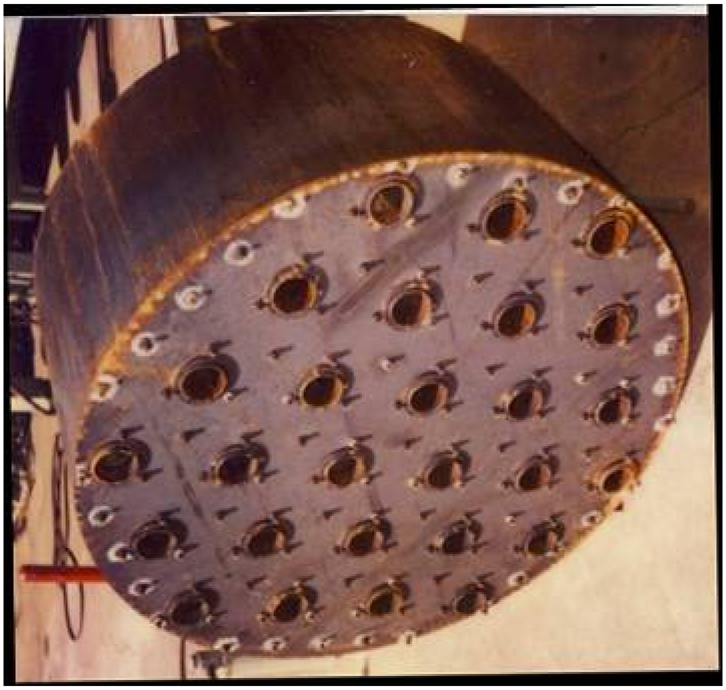


Figure VI
FRI$_{(SM)}$ TDP Distributor Layout
121 Pour Points, 48” id Tower

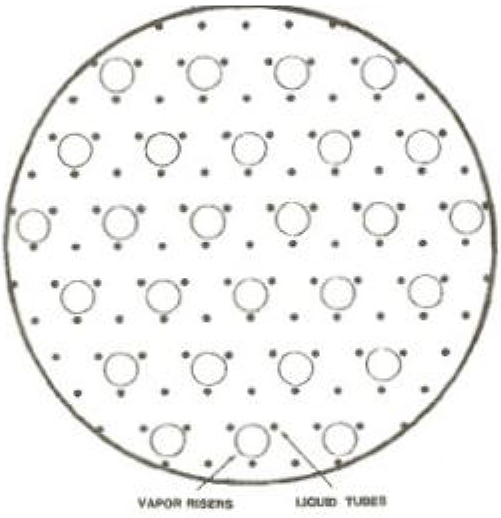


Figure VII
Distribution Pattern Quality, 91.1%
FRI$_{(SM)}$ TDP Distributor, 48" Tower
Analysis Provided by Joshi Samuel of Amistco Separation Prod.
Moore-Rukovena Method-WelChem Program

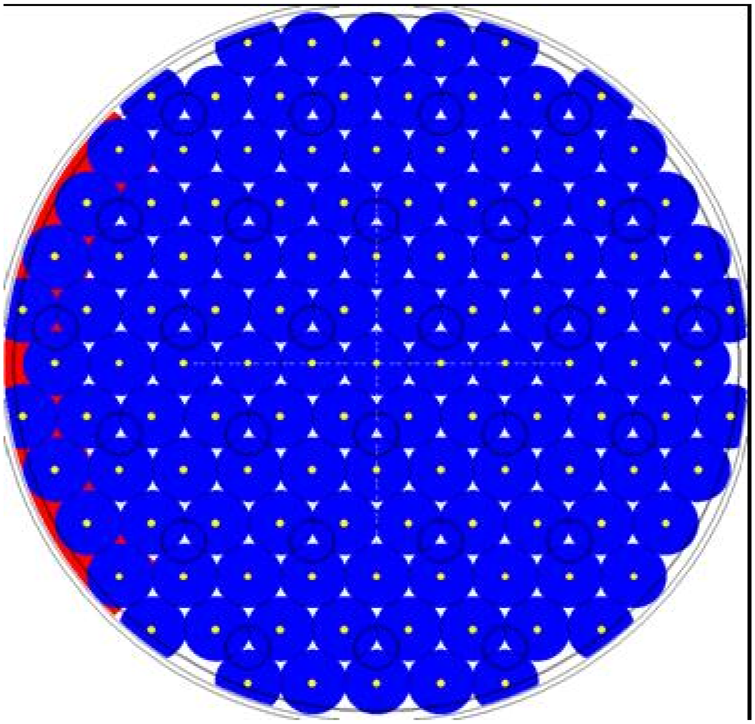


Figure VIII
FRI$_{(SM)}$ Small TDP Distributor
16 Pour Points, 16.9" id Tower

Figure IX
Distribution Pattern Quality, 73%
Small FRI$_{(SM)}$ TDP Distributor, 16.9" Tower
Analysis Provided by Joshi Samuel of Amistco Separation Prod.
Moore-Rukovena Method-WelChem Program

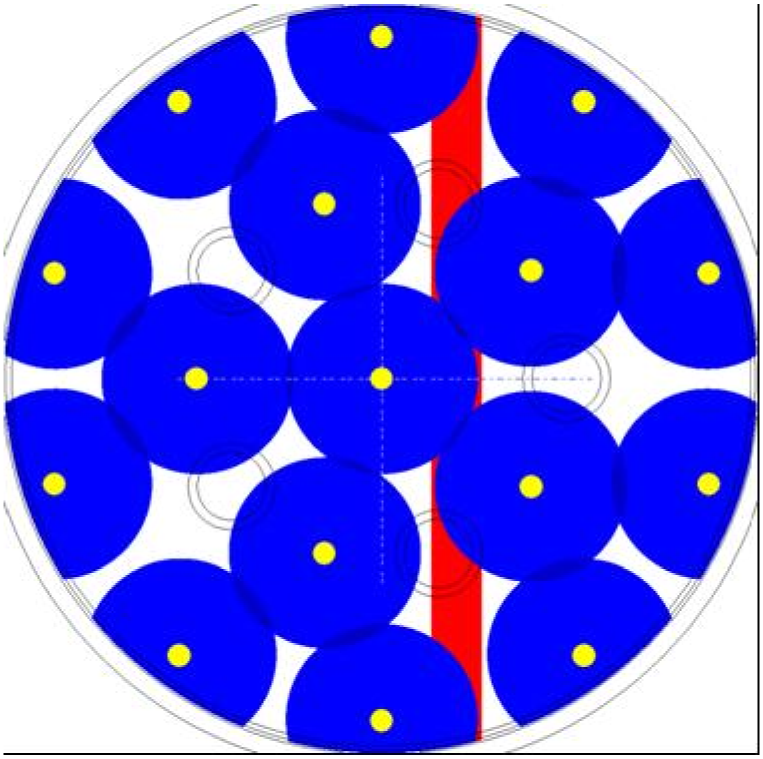
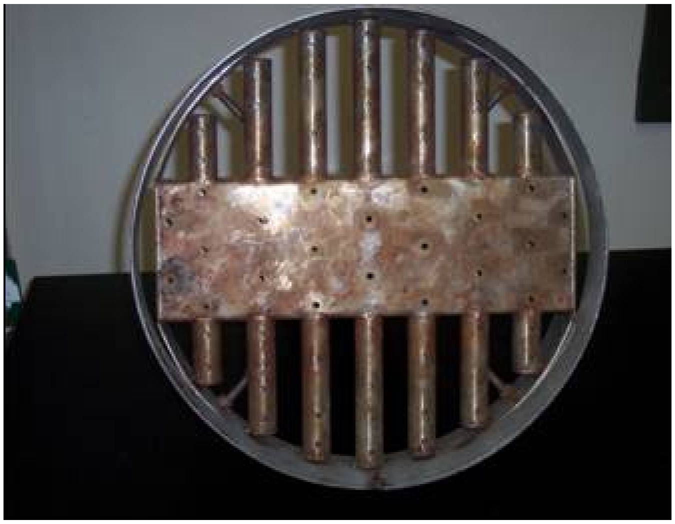


Figure X
Third Party Distributor
62 Pour Points, 16.9" id Tower



Unpublished: Presented at the Spring AIChE Meeting 2009, Tampa, FL Distillation Symposium

Figure XI
Distribution Pattern Quality, 72.6%
Third Party Distributor, 16.9" Tower
Analysis Provided by Joshi Samuel of Amistco Separation Prod.
Moore-Rukovena Method-WelChem Program

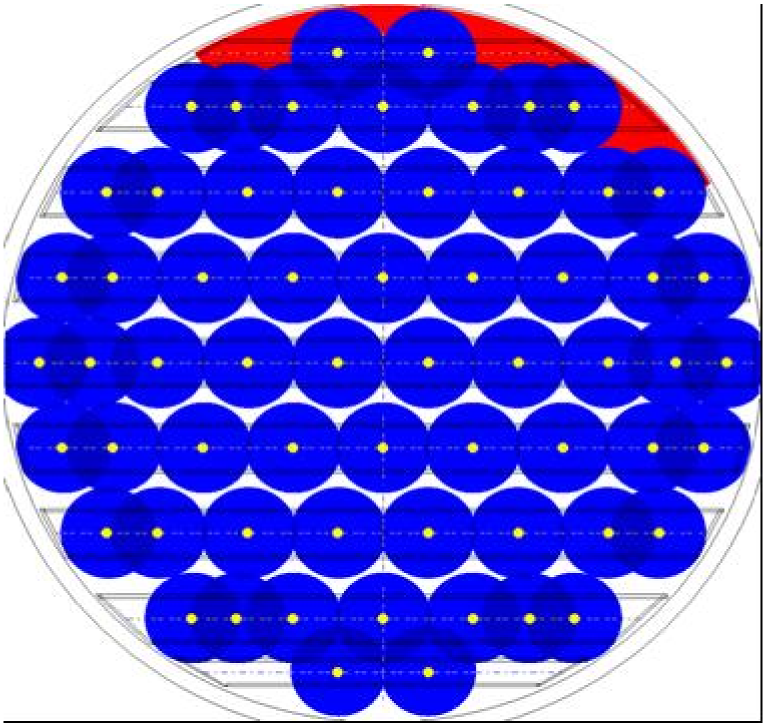


Figure XII
HETP vs. Maximum Useful Capacity Definition

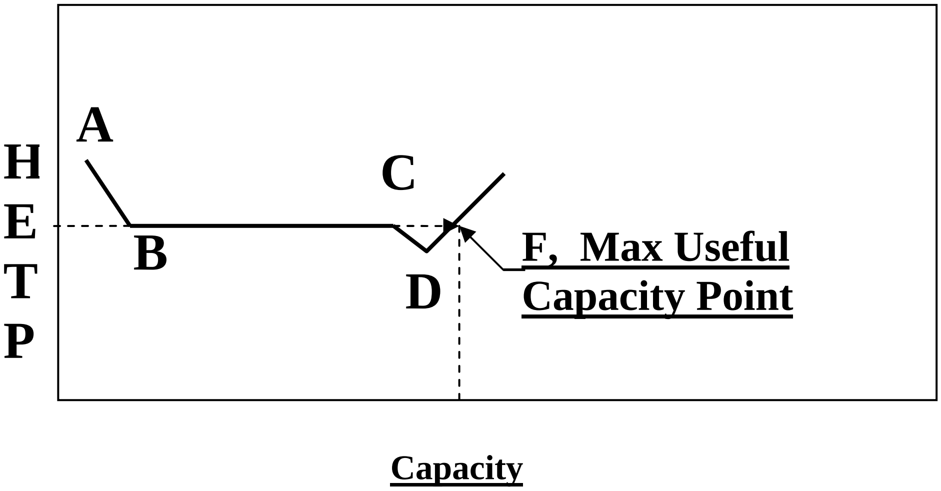


Figure XIII
Pour Points Density Effect on Theoretical Stages
1 in. Pall Rings, FRI$_{(SM)}$ 48” Tower

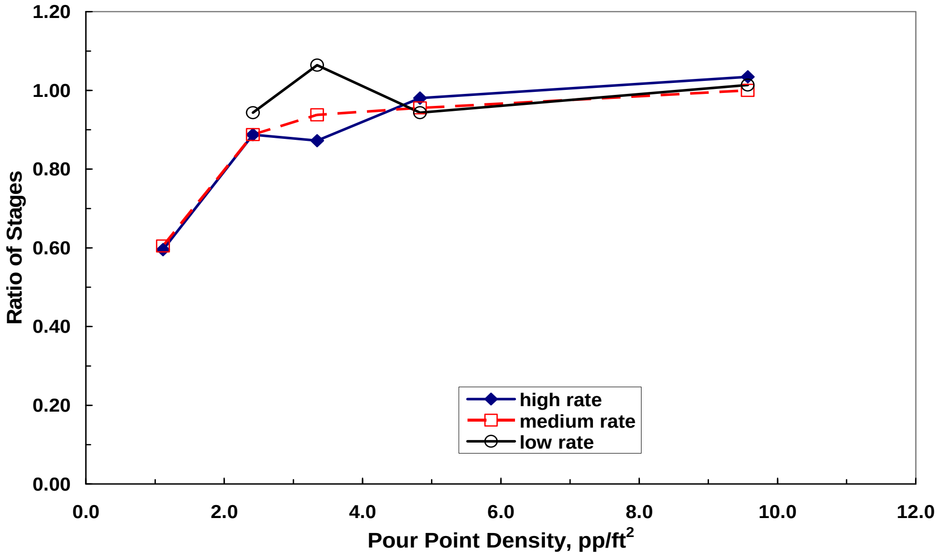


Figure XIV
Random Distributor Liquid Maldistribution Effects
vs.
Zonal Distributor Liquid Maldistribution Effects

FRI$_{(SM)}$ 48” Tower, ± 12.5% Variation

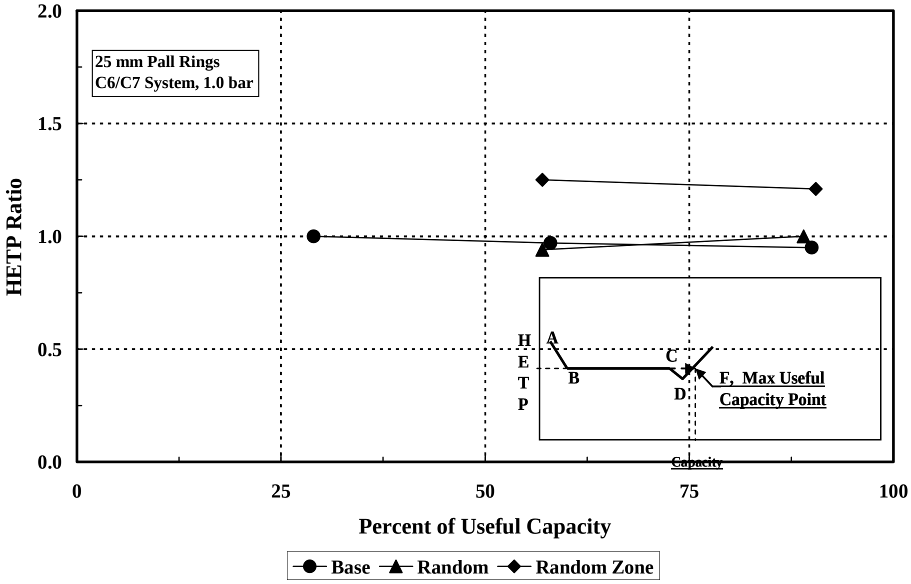


Table I

Distributor/Packing Performance

1 inch Metal Pall Rings; 24 psia; Cyclohexane/n-Heptane (C_6/C_7)

Distributor	Tower		Pour Pts	Pattern Rating	Packing
Type	ID, in	Pk. Depth, ft	Pts/ft^2	%	HETP, in
TDP	48	12	9.7	91.1	15
V-Notch	48	12	?	30 (Guestimate)	24
TDP	16.9	8	10.3	73	19
Third Pty	16.9	8	39.9	72.6	18