Paper 20d

Atmospheric Distillation Process

Fundamental Concepts

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1.0 Abstract

Crude oil processing is the first step in the petroleum refinery. This distillation occurs in the refinery crude unit. The objectives of the unit include rejection of major contaminants and an initial cut of the crude oil into streams for further processing. Understanding the fundamentals of crude unit operation is critical to effective design, modification, operation and troubleshooting refinery crude units. The following discussion covers the following major objectives;

- Introduce fundamental performance parameters for yield, separation, and heat recovery.
- Define the three basic crude tower heat-recovery configurations.
- Develop basic understanding of tower internal vapor-liquid loadings and their effect on fractionation performance.
- Introduce a starting point for comparing the different heat-recovery configurations.

Three main performance measures describe atmospheric crude tower operation;

- Cutpoint describes yield.
- Gap-overlap describes fractionation effectiveness.
- Feed preheat describes heat recovery.

The basic approach in yield analysis is the cut-point evaluation. This links unit performance to standard measures used in crude assays.

Gap-overlap is the major concept in separation analysis. Separation between products is a key to meeting specification requirements. Separation varies with the number of stages available for a separation and the internal vapor and liquid traffic.

Feed preheat is the best overall measure of heat recovery performance. Most heat recovery from the crude atmospheric tower heats the unit feed. The hotter the unit feed upstream of the final fired heater, the more effective the heat recovery.

Three configurations of crude units are shown to illustrate the effect of internal liquid and vapor traffic in the tower on fractionation effectiveness. The first uses a limiting case of no side-heat recovery from the tower. All heat rejection occurs in the overhead. The second and third configurations use circulating liquid streams for improved heat recovery. One option uses a pumparound liquid that returns above its draw point. The other option uses a pumpdown liquid that returns below its draw point.

Inherent unit performance in atmospheric crude distillation is a balance of heat recovery versus product separation. Steps that improve heat integration degrade product separation. Steps that improve product separation increase heat losses. Depending upon the constraints imposed by the overall refinery objectives, some operating envelope will be available for balancing heat recovery versus product separation.

The heat balance versus product separation ties back to the gap-overlap analysis. In most units, the heat balance tightly links to separation performance. Understanding how heat recovery links to gap-overlap is key to understanding crude unit constraints.

2.0 Objectives

Crude distillation has well established fundamentals. The basic approach to atmospheric crude towers can be traced back to Packie [1941] and Watkins [1969, 1973]. Important work has occurred since them. Most of it has focused on standardizing calculation methods for thermodynamic properties and distillation conversions. The advent of modern software methods has made current memory of Packie and Watkins recede into the background. Nevertheless, the fundamentals remain the same. The objective here is to create an updated explanation of the fundamentals using current tools available to the engineer in industry. Foremost among those tools is the process simulator.

In operation, the working atmospheric crude distillation column must meet three major processing objectives;

- Initial separation of the crude oil for downstream processing.
- Heat recovery to reduce investment required and to reduce energy costs.
- Feed preparation for the downstream units.

The balance between separation and heat recovery sets unit performance. Separation performance is measured by a gap-overlap comparison or by product property specifications. Ultimately, heat recovery is measured by the temperature rise of crude feed or by heat recovery to other utilities. Feed preparation to the downstream vacuum unit adds a third performance parameter – overall unit yield. Yield on atmospheric towers is normally expressed as a cut-point.

3.0 Performance Evaluation

Performance evaluation of crude units focuses on the three objectives. This paper discusses separation versus energy recovery; but performance measures for all three areas must be understood to avoid confusion. Other work focuses more directly on energy recovery [Sloley 2014] and yield [Sloley 2013].

3.1 Gap-Overlap (Separation)

Many methods have been used to determine separation effectiveness in crude distillation. Gap-overlap is the method used here. This is the most common practice and can be readily determined. The gap-overlap is a measure of separation between two adjacent products from the atmospheric crude tower. The heavy cut is the lower product and has the higher molecular weight. The lighter product is the upper product and has the lower molecular weight. Both gap and overlap are defined by:

$$gap\ or\ overlap_{5/95} = ASTM\ D86_{5vol\%}\ Temp\ of\ Heavy\ Cut - ASTM\ D86_{95vol\%}\ Temp\ of\ Light\ Cut$$

A positive number is a gap. A negative number is an overlap. Care must be taken in interpreting reported numbers. Some industry usage drops the negative sign on an overlap. The convention here is that gaps are always quoted as positive numbers and that overlaps are always quoted as negative numbers. The more positive the value of the number, the better the separation between the two streams.

Larger gap values represent more separation between the two products. The definition used here is based on an ASTM D86 distillation with a 5/95 gap because it uses the 5 volume percent point of the heavier product and the 95 volume percent point of the lighter product. This definition is the one most commonly used in the industry. However, various plants use alternate percent points, weight percent instead of volume percent, or use different ASTM distillation methods. All these variations are valid if done consistently. Historical comparisons or comparisons between different units must use a consistent basis.

Table 1 shows an example of selected distillation points for both ASTM D86 and TBP (True Boiling Point or ASTM D2892 equivalent) distillations for atmospheric tower products [1]. Table 2 shows the calculated 5/95 and 10/90 gap-overlap values for both methods. Very different gap-overlap values can be quoted for the same performance, depending upon the definition used. These results are for a unit operating at the lower end of typical performance ranges.

Typical D86 95/5 performance on a well operating unit is in the range:

Split		
Light naphtha-heavy naphtha	-60 to + 25°F	-33 to +14°C
Heavy naphtha-kerosene	0 to +50°F	0 to +28°C
Kerosene-diesel	-20 to +50°F	-11 to +28°C
Diesel-AGO	-50 to 0°F	-28 to 0°C
AGO-ARC	-200 to -100°F	-111 to -56°C

One weakness of the gap-overlap measure comes from the influence of sidestrippers and stripping sections on the 5 percent distillation point. Small changes in stripping can dramatically shift the 5 percent point. This may show up as a large change in gap-overlap. This is especially true for the light naphtha-heavy naphtha split and the AGO-ARC split [2]. Many units do not have or do not use a heavy naphtha sidestripper. Many others suffer from poor ARC stripping.

Nevertheless, the gap-overlap is still considered the basic measure of atmospheric column separation efficiency.

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1 Appendix A includes alternate tables and figures with metric units as required.

2 Appendix D includes definitions and abbreviations used.

3.2 Heater Inlet Temperature (Energy Recovery)

Refinery crude units remove heat from the distillation tower feed. Heat recovery effectiveness can be evaluated by monitoring the final feed temperature upstream of the fired heater. Higher feed preheat temperature equals higher thermal efficiency in the unit.

Units that include steam generators or that integrate with other parts of the plant present a more complex situation. Energy import to or export from the crude unit must be included in evaluation of thermal efficiency.

3.3 Cutpoint (Yield)

Cutpoint is a measure of unit yield. The definition of cutpoint is the TBP (ASTM D2892) distillation temperature that would achieve the same split between distillate products and bottoms product that the unit achieves. By definition, D2892 distillations are reported in atmospheric equivalent temperature. Either weight percent or volume percent can be used, however, the most common practice plots distillation data versus volume percent distilled.

As an example, Table 3 shows yields for a crude unit. Figure 1 shows the total distillate percentage on the crude TBP curve. The graphical solution shows that the example column has a cutpoint of 718.5°F (381.4°C).

4.0 Understanding Atmospheric Columns

The key to understanding crude columns is to understand that the atmospheric crude tower is a type of main fractionator. The important characteristics that distinguish main fractionators from other types of towers include:

- All the heat available for the distillation enters the tower with the feed. Feed usually comes from a fired heater or a preheat train.
- The tower has multiple heat removal zones using either pumparounds or pumpdowns.
- Multiple side draw products leave the towers.

All these characteristics make main fractionators different from classical distillation towers. Main fractionators have intimately linked heat and material balances. Understanding their operation requires tracking how heat and material balances affect each other.

The most important consequence for the analysis of atmospheric distillation in the crude unit is the limitation of heat input. Except in rare cases, main fractionators do not have reboilers. The combination of feed heat limits plus operating pressure set the maximum vaporization in the flash zone (tower feed entry area). Heat input limits also set maximum possible reflux rates. Maximum reflux rates limit the ability to separate the products.

Most crude units run to some feed limit; either maximum duty input or maximum temperature. Either of these limits imposes operating constraints on unit performance.

5.0 Basic Configurations

Watkins [1973] recognized three types of crude tower configurations:

- U-Towers or RO-Towers (Un-refluxed towers or overhead reflux only towers).
- A-Towers or PA-Towers (Absorption heat removal towers or pumparound towers).
- R-Towers or PD-Towers (Reflux heat removal towers or pumpdown towers).

Confusion arises because a plant may refer to all the streams entering and leaving the crude tower as reflux streams without taking into account the return location or whether they have heat removal. Watkins, in fact, defined ‘reflux’ as a liquid side draw that is drawn from the tower, cooled, and returned to the tower. This meaning remains in common use in the refining industry. Many

plants refer to this as a circulating reflux. For example, a plant may call the top pumparound circuit on the tower the TCR (top circulating reflux). In this sense, the term is ambiguous; the circulating reflux may still be either a pumparound or a pumpdown.

Here the following definitions will be strictly followed:

- Reflux only (RO); liquid returned to the top of the tower from the overhead system.
- Pumparound (PA); liquid drawn from the tower, cooled, and then returned to the tower at a stage *above* the liquid draw.
- Pumpdown (PD); liquid drawn from the tower, cooled, and then returned to the tower at the stage *below* the liquid draw.

In U-Towers, all heat removal is in the overhead condensers. Figure 2 illustrates a conceptual view of the U-Type configuration. The usage here refers to the U-Tower as a reflux only (RO) tower.

Both the A-Tower and the R-Tower use circulating refluxes. Figure 3 and Figure 4 show conceptual sketches of the A-Tower and R-Tower. Common industry usage refers to A-Towers as pumparound (PA) towers and R-Towers as pumpdown (PD) towers. Figure 5 illustrates the difference between them on an individual heat removal level. The PA-Tower (A-Tower or A-Type) takes liquid out of the tower, cools it, and returns it to a stage above the draw point. The PD-Tower (R-Tower or R-Type) takes the liquid out of the tower, cools it, and returns it to the stage below the draw. By definition used here, both a pumparound and a pumpdown must include heat removal.

Liquid removed from the tower and then returned to it without cooling is neither a pumparound nor a pumpdown. The purpose of liquid removal and return without any heat removal is to more conveniently meter and control internal liquid in the tower. Again, many plants refer to control streams as reflux or pumpdown streams. When discussing an existing unit with operating personnel, use the terminology familiar to the operating staff.

Figure 5 shows an active tray for the PA draw and a collector tray for the PD draw. This is arbitrary. Both PA and PD draws may be from either an active tray or a collector tray. However, regardless of the tray type, PA draws are usually a partial draw with internal overflow of liquid down the tower. For control precision, PA configurations can use a total draw with a controlled liquid flow down the tower. PD draws are always total draws.

When exceptions need to be made when discussing references, they will be clearly identified. Figure 6 shows the overall configuration of the RO-Tower (U-Type), PA-Tower (A-Type), and PD-Tower (R-Type).

5.1 RO-Towers (Reflux Only, Unrefluxed or U-Towers)

In an RO-Tower the overhead system provides all the heat removal. Side-draws take liquid out at each required product composition. All duty is removed at the condensing temperature of naphtha, the lightest product. Heat removal temperatures are low. Overall, RO-Towers have very poor heat recovery and large diameters for their capacity. Even on very small crude units of less than 2,000 bpd (318 m^3/day) capacity, RO-Towers are not used. The author has seen photographs of extremely small, truck-mounted crude towers of less than 200 bpd (32 m^3/day) capacity. These appear to be RO-Towers. It is useful to outline an RO-Tower to help understand crude units, however, they are not a practical application for crude distillation.

5.2 PA-Towers (Pumparound, Absorption or A-Towers)

The PA-Tower uses pumparound heat removal. Liquid is taken from the tower, cooled, and returned to a tray above the liquid draw point. Standard practice places the pumparound at the same location as a product draw. This gives up to five heat removal levels in the crude tower; one for

each major product plus the overhead condenser. Most crude units use PA configurations for heat removal. This configuration has effective heat recovery, simple control, and lowest overall capital cost.

5.3 PD-Towers (Pumpdown, Refluxed or R-Towers)

The PD-Tower uses pumpdowns for heat removal. Liquid is taken from the tower, cooled, and returned to the tray immediately below the liquid draw point. Standard practice has the pumpdown at the same location as a product draw. Few modern crude units use PD configurations. While the configuration can achieve effective heat recovery, capital cost is higher than for a PA-unit, and control can be very challenging.

6.0 Comparison Basis

To illustrate atmospheric crude tower operation a comparison will cover the three major types of crude tower heat-recovery configurations using a 100,000 bpd (15,900 m^3/day) unit. The comparison uses the same configuration and constraints as described in previous work [Sloley 2013, Appendix B].

The major product quality specifications are on the 95% points of the streams. The controlling specifications are overhead temperature (implies a 95% point for light naphtha); heavy naphtha 95% temperature; kerosene flash (light end) and 99% temperature; and diesel flash (light end) and 95% temperature. AGO draw is varied to meet minimum liquid wetting rates required by the tower internals below the AGO draw. Appendix E includes full details.

6.1 Backmixing and Subcooling Compensation

PA-Towers (A-Type) have backmixing of heavy liquid with lighter material further up the tower. Both PA-Towers (A-Type) and PD-Towers (R-Type) return subcooled liquid to the tower. Both backmixing and subcooled liquid return create thermodynamic inefficiencies. The tables and figures show two comparisons.

One comparison has the same number of total stages in the RO-Tower (U-Type), PA-Tower (A-Type) and PD-Tower (R-Type). The purpose of this analysis is to allow for direct visual comparison of vapor and liquid profiles on a stage-by-stage basis.

Compared to the RO-Tower (U-Type), two stages have been added for each PA heat removal level and one stage has been added for each PD heat removal level. The stages added are to make the fractionation effectiveness of each configuration approximately equal to a 41-stage RO-Tower (U-Type). This gives 49 total stages for PA-Tower (A-Type) and 44 total stages for the PD-Tower (R-Type). For consistency with previous work [Sloley 2014], the PA-Tower case is labeled PA-2 and the PD-Tower case is labeled PD-2.

6.2 Tower Sizing

All comparisons use a tray tower. For the same capacity, a new unit costs less when using a tower with trays. Packed towers have more capacity for the same vessel diameter, but cost more. Packed towers require an entire system of components in addition to the packing. Packing includes supports, hold-downs, liquid distributors, and liquid collectors. Each time a side draw or pumparound return is added, an entire set of support-collector-liquid distributor-hold-down is required. The final cost of a packed tower, when built new, is higher than a trayed tower.

The one exception to this is the wash zone between the AGO product and the flash zone. This section should be packed even in a new tower. The packing works effectively at lower liquid rates

than trays can work. The lower liquid rate allows for higher yield at the same flash zone conditions. A full discussion of this is covered by other work.

The comparison of the different heat removal options includes determining the required column diameter. Diameters shown are based on using conventional valve trays with a 24-inch (61 cm) tray spacing. In this system, the main factor influencing required column diameter is the tray vapor handling rate. Liquid rates in all the fractionation sections are relatively low for the diameter.

The pumparound sections can have much higher liquid rates. Pumparounds can have enough liquid that the liquid load affects the tray sizing. For pumparounds, the tray spacing was allowed to increase to 30 inches (76 cm) if that kept the pumparound tray the same diameter as the trays immediately below it.

6.3 Pressure Profiles

Trays have significant pressure drop per tray. Adding trays to a PA-Tower (A-type) or a PD-Tower (R-type) changes the tower pressure profile. Most authors ignore the consequences of modified pressure profiles when comparing tower types. In contrast, the analysis here will modify the tower pressure profile when adding stages.

Improved heat recovery reduces vapor load from the tower to the overhead condenser. Since the purpose of the PA-Tower and PD-Tower is to improve heat recovery, they can benefit from a reduced overhead condenser pressure drop to compensate for the extra trays in the column.

The overhead drum pressure and the flash zone pressure is kept constant in all comparisons. The changed pressure profile is handled by including a modified pressure drop in the overhead condenser. Hence, all comparisons have a fixed overhead drum pressure, a variable tower top stage pressure, and a fixed flash zone pressure. This keeps the overall cutpoint (yield) constant for a fixed feed temperature.

This basis reasonably approximates real unit performance. The pressure drop through the overhead condensers is a significant fraction of the overall pressure profile. Overhead rate changes will cause significant pressure profile changes. The choice being made here is that as overhead duty drops, overhead exchanger sizes go down. As overhead exchanger sizes go down, some of the credit of the reduced duty will be taken in reduced pressure drop as well as in reduced surface area.

6.4 Loading Profiles

The comparisons present vapor-liquid loading profiles for each case. The vapor inside the tower comes from both steam and hydrocarbons vapor. Water enters the system from desalter carryover, soluble water from the feed, atmospheric tower stripping steam, and side-stripper steam. The loading profiles shown for vapor rates, liquid rates, and vapor-liquid ratios are all on a steam-free basis. The differences between the options due to different steam rates and different steam entry points are extremely minor and can be ignored.

7.0 RO-Tower Analysis (Reflux Only or U-Tower)

All the heat removal in an RO-Tower is in the overhead system. Side draws take liquid out as it descends the tower. Liquid composition varies with the draw tray location. Figure 7 shows internal liquid and vapor rates in the RO-Tower for the section of the tower above the feed.

All liquid in the tower comes from the overhead condenser. As liquid descends the tower, its composition changes. The changes in composition and temperature cause a gradual decrease in

liquid rate [3]. At product draw locations, liquid rate rapidly drops. All down the tower, the ratio of liquid-to-vapor (L/V ratio) drops. Distillation performance depends upon molar ratios of liquid-to-vapor. At low L/V ratios, distillation performance is poor [4].

The low molar heat of vaporization of the low molecular weight material at the top of the column requires a large vapor volume to carry all the mass to the condenser. The required column diameter is largest at the top. Figure 4 includes the required column diameter along with the vapor and liquid loads.

Because all the liquid comes from the overhead condenser, the RO-Tower has the maximum possible reflux at every stage. This gives the RO-Tower the best fractionation performance possible. However, its poor heat recovery outweighs the benefits of maximum fractionation.

8.0 PA-Tower Analysis (Pumparound or A-Tower)

PA-Towers remove heat by circulating liquid streams. In PA-Towers, the pumparound liquid returns to a stage above its draw. Watkins' use of the term A-type comes from considering the heat removal as an absorption operation. The absorption mixing of cold, higher molecular weight liquid with partially fractionated liquid inside the tower reduces the separation effectiveness of the pumparound trays.

The pumparound heat removal also reduces internal liquid traffic higher up the tower. Liquid rate and stages determine separation effectiveness. With lower liquid rates, either more stages are required to compensate or less separation must be accepted. For design, the engineer can optimize between stages and product quality and product yields.

An operating unit, however, must work within constraints of what is already built. Once built, accepting less separation with increased heat recovery is the operating option.

Packie [1941] first published curves for separation versus reflux. Modern simulation software allows rapid evaluation tailored to specific plants and feeds.

When accepting less separation, the product quality requirements do not change. When adding pumparounds, separations between adjacent products degrade. Since product separation depends upon both internal L/V ratio and stages, adding stages can compensate for lower internal L/V ratios. Regretfully, economic levels of heat integration reduce the internal reflux ratio below the minimum required for a PA-Tower to match the performance of the RO-Tower, even with infinite trays.

Table 4 includes two cases. Case PA-1 is the conversion from a RO-Tower (U-type) to a PA-Tower (A-type) with no additional stages added. Case PA-2 is the conversion to a PA-Tower (A-type) with two additional stages added per pumparound. Since the tower has four pumparounds, this adds eight total stages to the tower. Figure 8 shows profiles for the liquid load, vapor load, and column diameter for case PA-1.

9.0 PD-Tower Analysis (Pumpdown or R-Tower)

PD-Towers also remove heat by circulating liquid streams. In PD-Towers, the pumpdown liquid returns to a stage below its draw. The terminology R-type comes from considering heat removal as analogous to a conventional reflux operation with a subcooled liquid.

In contrast to PA-Towers, PD-Towers do not have back-mixing of the liquid compositions. The PD-Tower has more fractionation effectiveness for the same number of stages in the atmospheric

3 Appendix B for details.
4 Appendix C for details.

column. Concern on back-mixing drove some designers to use PD-Towers in the late 1960s through the late 1980s.

Table 4 includes two PD-tower configurations. Case PD-1 is the conversion from a RO-Tower (U-Type) to a PD-Tower (R-Type) with no additional stages added. Case PD-2 is the conversion to a PD-Tower (R-Type) with one additional stage added per pumpdown. Since the tower has three pumpdowns, this adds three total stages to the tower. Figure 9 shows profiles for the liquid load, vapor load, and column diameter for case PD-1. This case has the same number of stages at the RO-Tower (U-Type) example.

The PD-Tower has two heat removal limits. The tabulated results include both limits.

First, the minimum possible return temperature on the pumpdown streams limits heat removal at each level. Since the maximum liquid rate is set by the net liquid not taken as a product, the minimum return temperature sets a maximum heat removal duty.

Second, an AGO pumpdown would be condensing material that goes out the tower bottoms. The internal liquid rate below the AGO draw is set by equipment mechanical limits. AGO pumpdown duty is also constrained by this limit. AGO pumpdowns are not economic because they have a relatively small duty, column material balance forces the duty to be taken from the pumpdown above, and their incremental capital costs are high. As a result, no AGO pumparound is included in the comparisons.

10. Fractionation Performance

L/V ratio is a key element in fractionation performance. Figure 10 and Figure 11 plot the L/V ratios for the RO-Tower (U-Type), PA-Tower (A-Type), and the PD-Tower (R-Type). Figure 10 shows the ratios against a logarithmic scale and Figure 11 shows the ratios against a linear scale. Figure 10 emphasizes the very low L/V ratios available to separate diesel-AGO and AGO-residue. Figure 11 emphasizes the difference in potential splits between LN-HN, HN-Kero, and Kero-Diesel.

In all cases, L/V ratios decrease going down the column. Separation performance in atmospheric crude columns degrades in going from lighter to heavier products. This performance is inherent in the system. The trend holds regardless of heat integration type.

For heavier products from the atmospheric crude tower, less fractionation is possible. Gaps get worse (and turn into overlaps) when descending the crude column. Specific heat-integration may result in reversing this trend between two adjacent products, but the overall trend is always from better to worse fractionation.

For lighter products from the atmospheric crude tower, more fractionation is possible. Naphtha-kerosene is typically the best separation in the crude column. With light naphtha versus heavy naphtha general rules are more difficult to state. Many units with heavy naphtha products do not side-strip the heavy naphtha. The example here does not have a heavy naphtha sidestripper. This produces heavy naphtha with a very long light-end distillation tail. With a side-stripper, the LN-HN overlaps shown would turn into gaps.

11.0 Heat Integration Performance

Heat integration in crude towers is extremely effective in reducing capital investment and energy costs. Capital investment savings come from reduced tower diameter, smaller utility systems for heat rejection, and smaller fired heaters. Energy savings come directly from heat recovery.

Figure 12 shows required column diameter versus configuration. Overall, the PA-Tower (A-type) has the smallest tower diameter for the same capacity. When comparing columns of the same diameter, the PA-Tower has the largest capacity. The key point is that the PA-Tower can easily

reduce vapor volume by removing duty further down the column. This comes at a cost. Regardless of the tower configuration, the lower down the tower that duty is removed, the greater the fractionation penalty.

The PD-Tower (R-Type) suffers from limited heat removal capability. First, the liquid rate available for heat removal is limited to the net liquid from the tower. The limited liquid rate and temperature pinches on the PD-Tower restrict its heat removal capability. Additionally, the lack of the lower pumparound at the AGO also restricts the ability for heat removal. Both these factors combine to make PD-Towers less capable of energy recovery.

The units shown here use aggressive heat recovery. Less aggressive heat integration reduces the disadvantages of the PD-Tower. However, the disadvantages never disappear. PD-Tower units have lower temperature approaches in the exchangers than PA-Tower units. Considering the entire unit, atmospheric crude units include significant investment in the heat exchangers and pumping systems. PA-Towers are clearly superior on a total unit investment cost and have lower operating costs for the same investment.

Further work will more fully explore the PA-Tower, PD-Tower and other heat recovery options [Sloley 2014].

12.0 Conclusions

The following measures define atmospheric crude tower performance:

- Yield, measured by cutpoint.
- Heat recovery, measured by temperature rise of the feed.
- Separation, measured by gap-overlap.

All three must be understood for effective design and operation of atmospheric crude distillation. This work focuses on process fundamentals in the trade-off of heat recovery versus fractionation. Previous work [Sloley 2013] has focused on basic choices for yield. Upcoming work focuses on basic choices for heat recovery [Sloley 2014].

All options available must contend with decreasing fractionation effectiveness for the lower product draws from the atmospheric crude column. All options must also balance the fact that steps that improve heat integration degrade product separation. Steps that improve product separation increase heat losses. However, depending upon the constraints imposed by the overall refinery objectives, some operating envelope will be available for balancing heat recovery versus product separation.

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Appendix A – E Removed for shortened version

Volume Percent	Light Naphtha	Heavy Naphtha	Kerosene	Diesel	AGO	ARC
	°F	°F	°F	°F	°F	°F
ASTM D86						
5		280	402	466	613	670
10		326	427	535	651	739
90	313	389	524	628	791	
95	327	400	536	640	809	
TBP						
5		255	376	460	596	668
10		296	403	512	634	724
90	334	409	554	663	831	
95	353	419	570	677	867	

Table 1 Product Distillation Example

Heavy Cut	Heavy Naphtha	Kerosene	Diesel	AGO	ARC
Light Cut	Light Naphtha	Heavy Naphtha	Kerosene	Diesel	AGO
	°F	°F	°F	°F	°F
ASTM D86					
5/95	280-327= -57	402-400= 2	466-536= -70	613-640= -27	670-809= -139
10/90	326-313= 13	427-389= 38	535-524= 11	651-628= 23	739-791= -52
TBP					
5/95	255-353= -98	376-419= -43	460-570= -110	596-677= -81	668-867= -199
10/90	296-334= -38	403-409= -6	512-554= -42	634-663= -29	724-831= -107

Table 2 Gap-Overlap examples

Stream	Rate Bpd	Rate Cmpd
Crude	100,000	15,898
Atmospheric Tower		
Crude gas	-	-
Light naphtha	21,651	3,442
Heavy naphtha	4,719	750
Kerosene	14,593	2,320
Diesel	8,929	1,420
Atmospheric Gas oil	7,562	1,202
Total distillate	57,456	9,134
Atmospheric reduced crude	42,544	6,763

Table 3 Example unit yields

		Configuration				
		RO (U-type)	PA-1 (A-type)	PA-2 (A-type)	PD-1 (R-type)	PD-2 (R-type)
Stages	Above FZ	41	41	49	41	44
Yields	Bpd					
Light Nap		20,634	21,582	22,116	21,350	21,628
Heavy Nap		6,769	4,226	3,698	4,934	4,656
Kerosene		14,139	14,556	14,936	14,569	14,786
Diesel		8,282	9,340	8,975	9,104	8,852
AGO		7,624	7,747	7,725	7,493	7,528
Total Distillates		57,447	57,451	57,449	57,450	57,449
ARC		42,553	42,549	42,551	42,550	42,551
Gap-Over	D86 95/5					
LN-HN		8.7	-54.7	-55.7	-51.8	-52.8
HN-Kero		24.4	-12.0	-10.4	-2.1	-1.4
Kero-Dies		-52.2	-87.0	-87.9	-88.8	-90.0
Dies-AGO		-27.0	-35.2	-34.6	-26.7	-26.7
Duty	MB/hr					
Condenser		230.2	120.4	121.8	137.4	130.9
HN Circuit		-	21.0	21.0	35.9	34.3
Kero Circuit		-	36.0	36.0	34.9	32.8
Dies Circuit		-	42.0	42.0	43.2	41.2
AGO Circuit		-	20.0	20.0	-	-
Total Heat Removal		230.2	229.4	240.8	251.4	239.2
Total Side Heat Removal		-	119.0	119.0	114.0	108.3
Temps	°F Draw – Return					
Condenser		300 – 100	300 – 100	300 – 100	300 – 100	300 – 100
HN Circuit			378 – 274	377 – 274	376 – 120	376 – 120
Kero Circuit			460 – 338	459 – 337	467 – 120	466 – 120
Dies Circuit			569 – 412	569 – 412	569 – 150	568 – 150
AGO Circuit			648 – 538	648 – 538		

Table 4 Separation, Yield, and Heat Recovery Performance of Different Heat-Integration Configurations

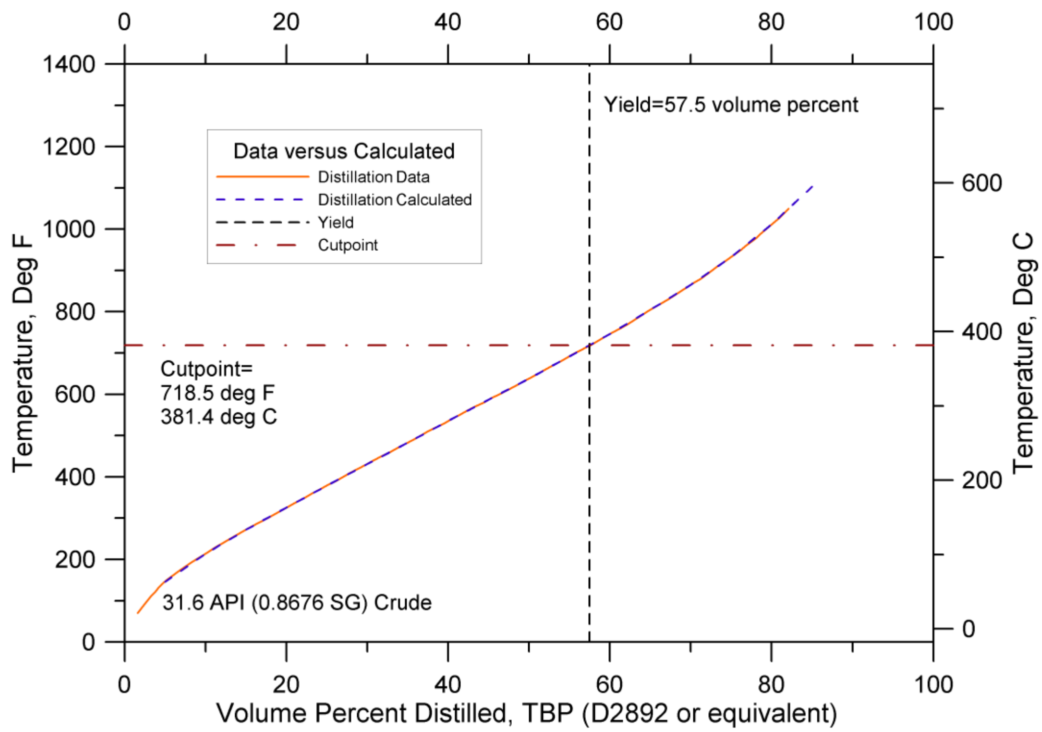

Figure 1 Cutpoint Example

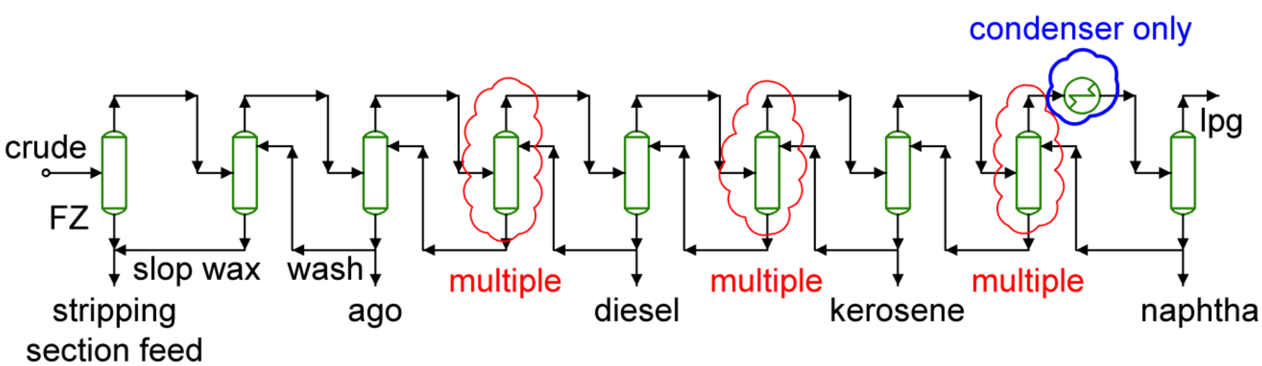

Figure 2 Reflux Only (RO)-Tower Concept

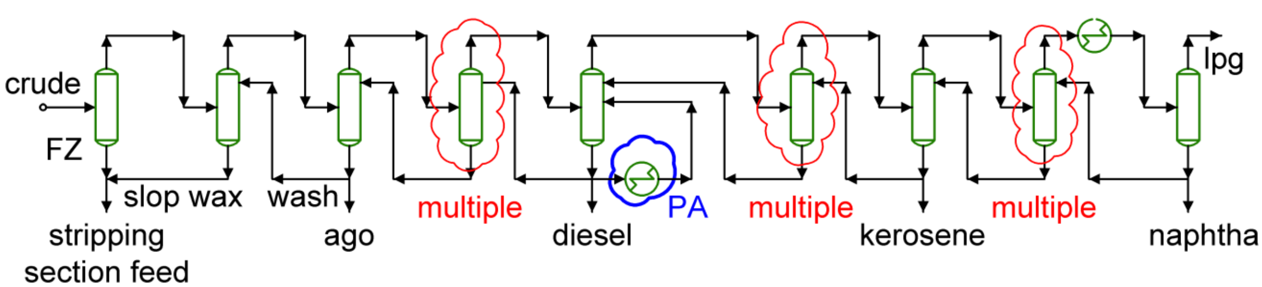

Figure 3 Pumparound (PA)-Tower Concept

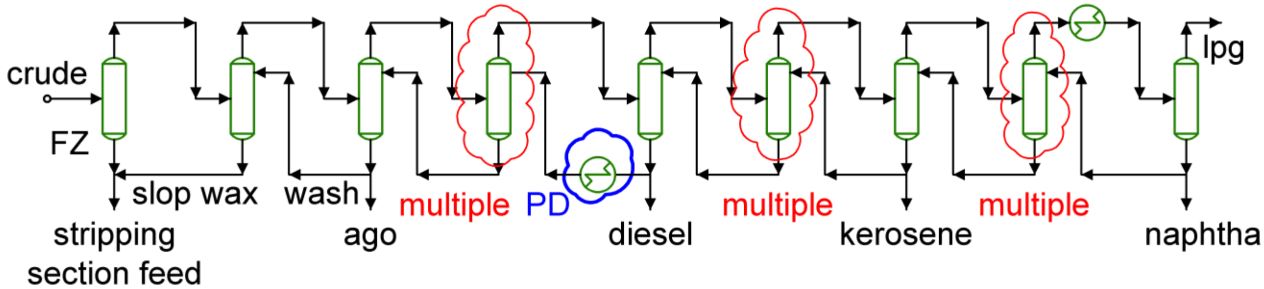

Figure 4 Pumpdown (PD)-Tower Concept

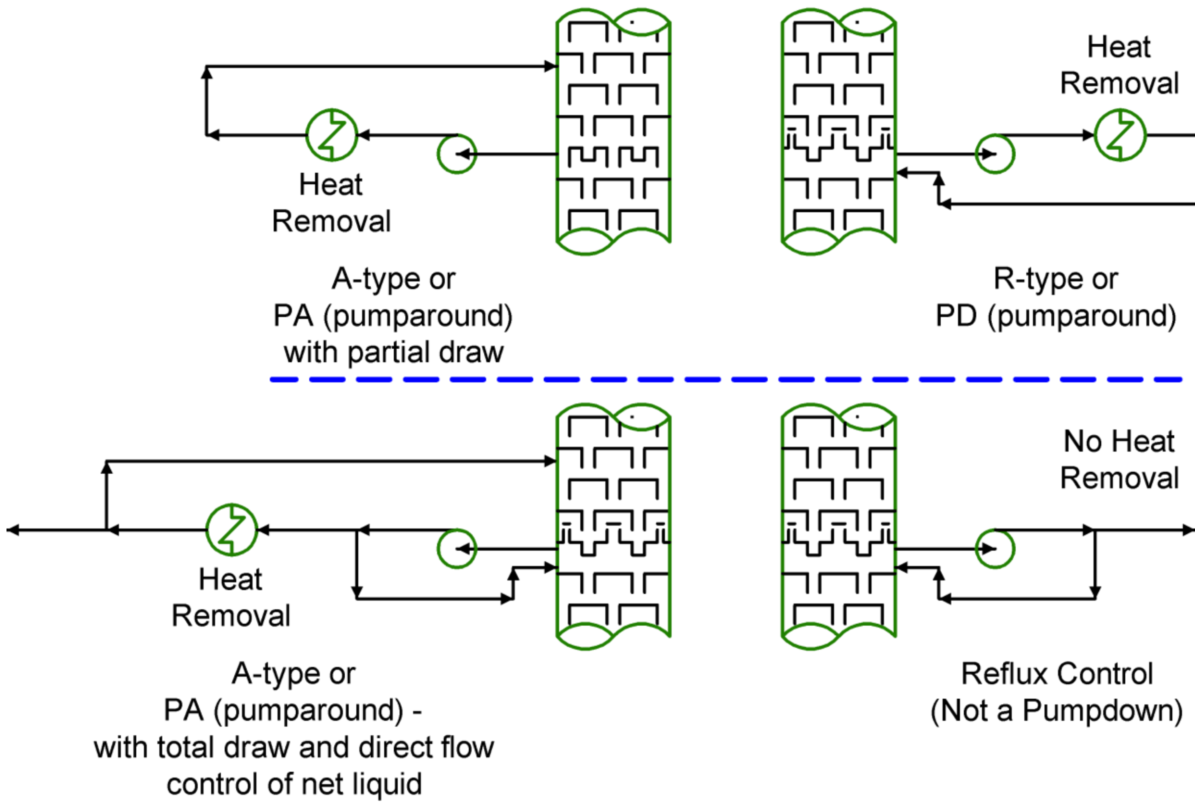

Figure 5 Heat Removal Type Definitions

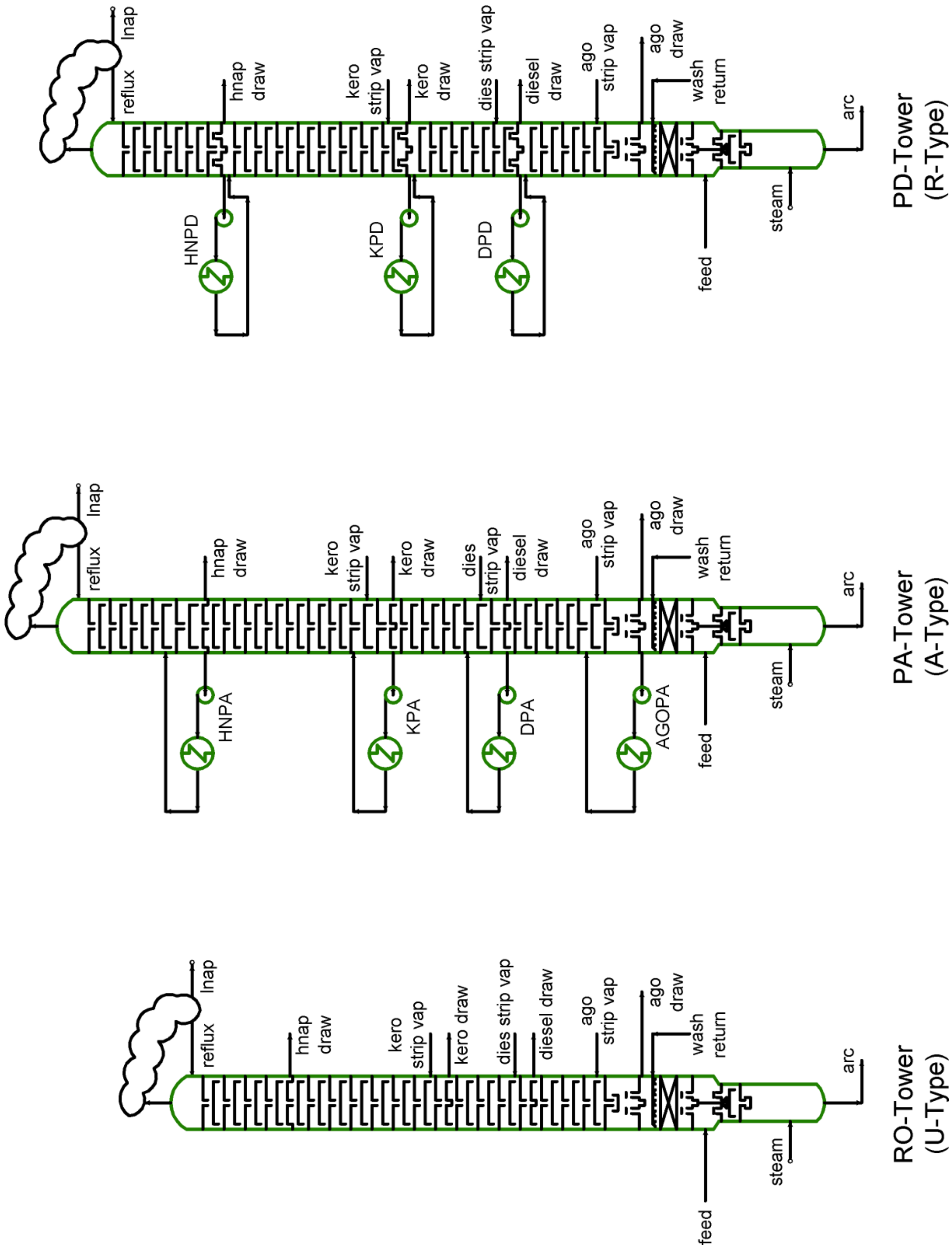

Figure 6 Tower Configurations

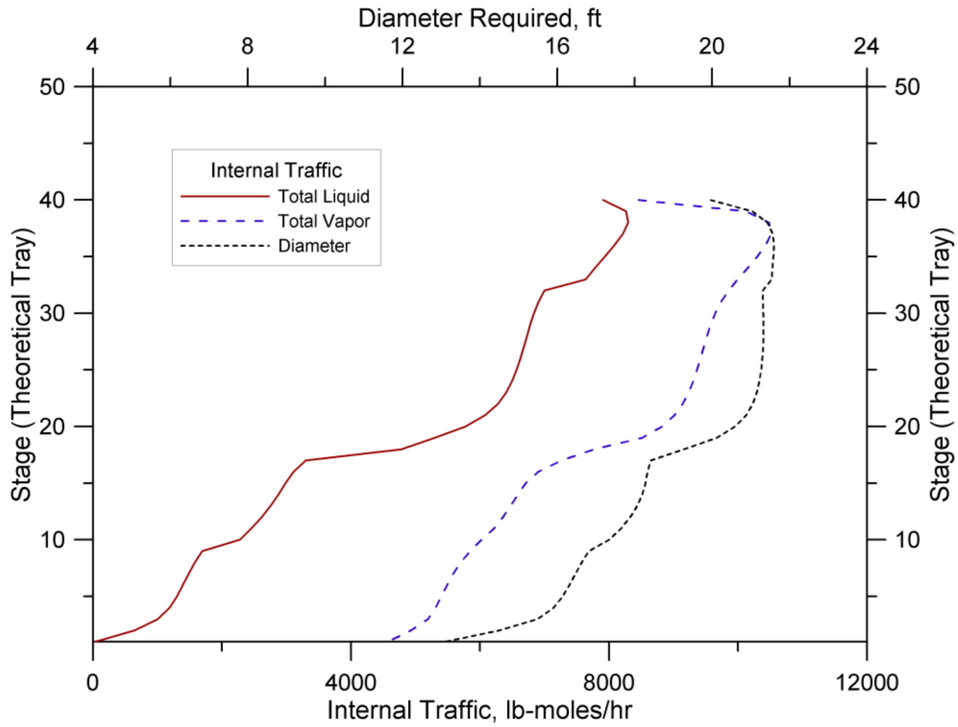

Figure 7 Loading and Diameter – RO-Tower (U-Type)

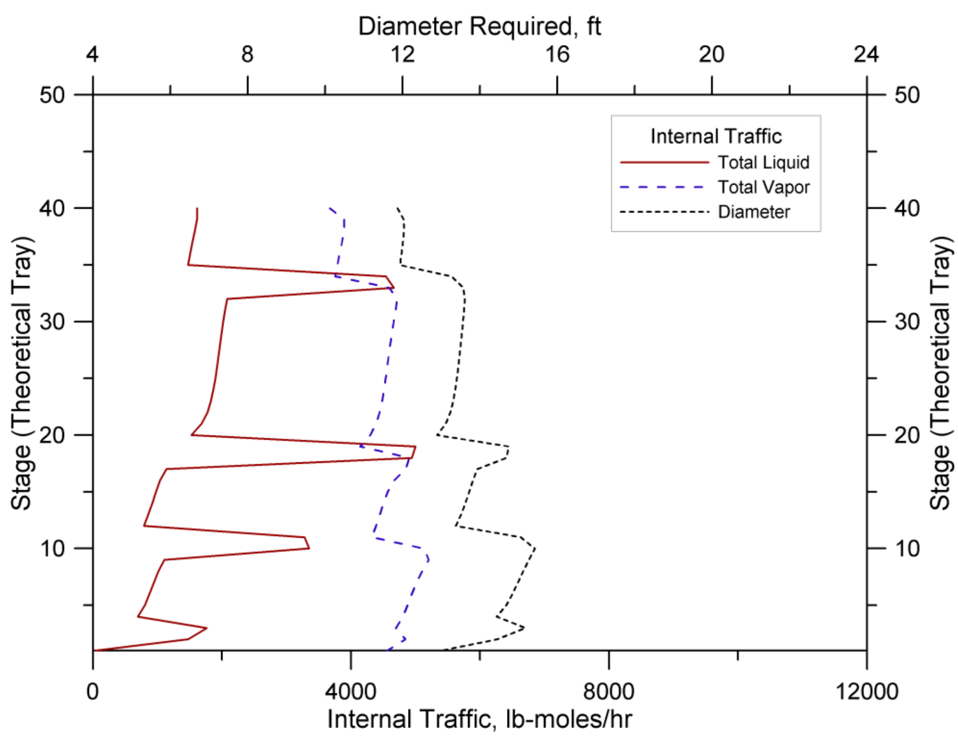

Figure 8 Loading and Diameter – PA-Tower (A-Type) (Stages equal to RO-Tower in Figure 7)

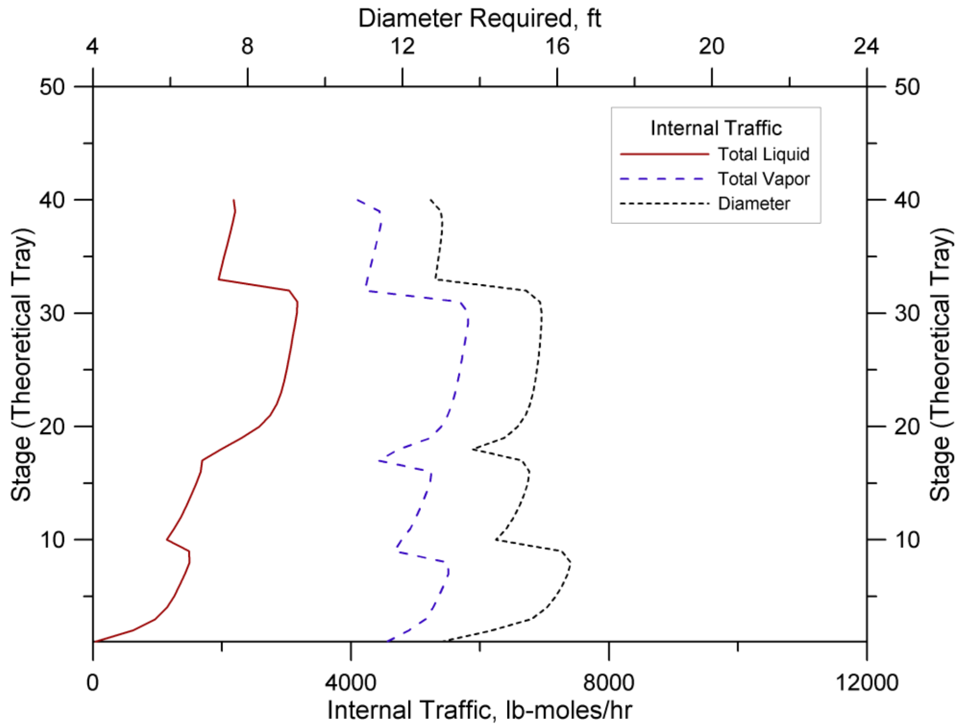

Figure 9 Loading and Diameter – PD-Tower (R-Type) (Stages equal to RO-Tower in Figure 7)

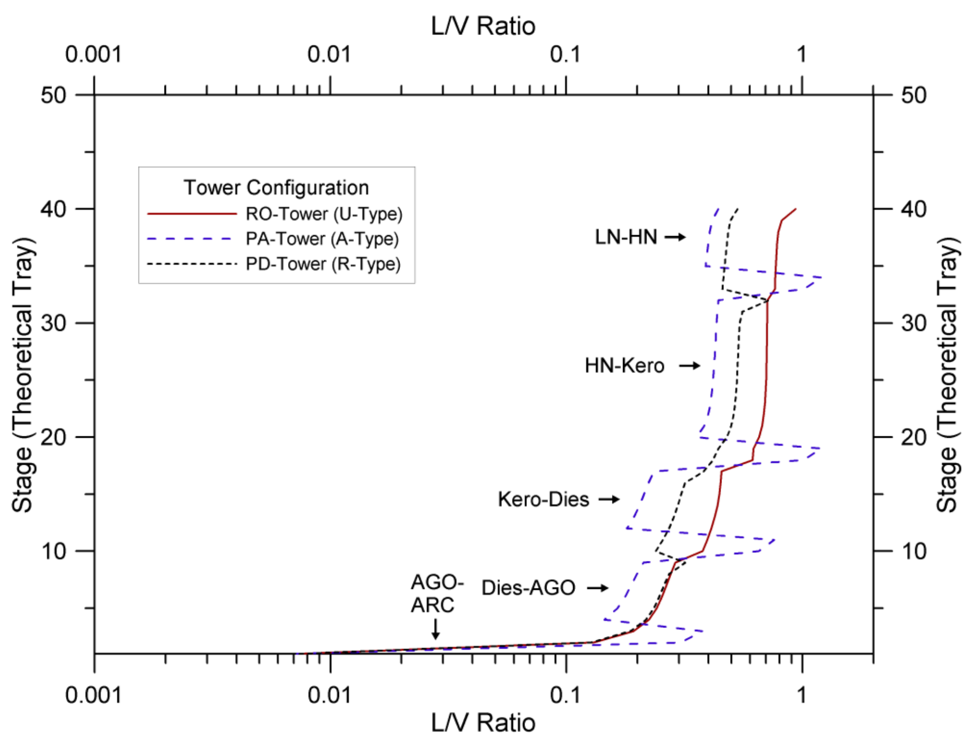

Figure 10 L/V Ratios versus stage for different configurations

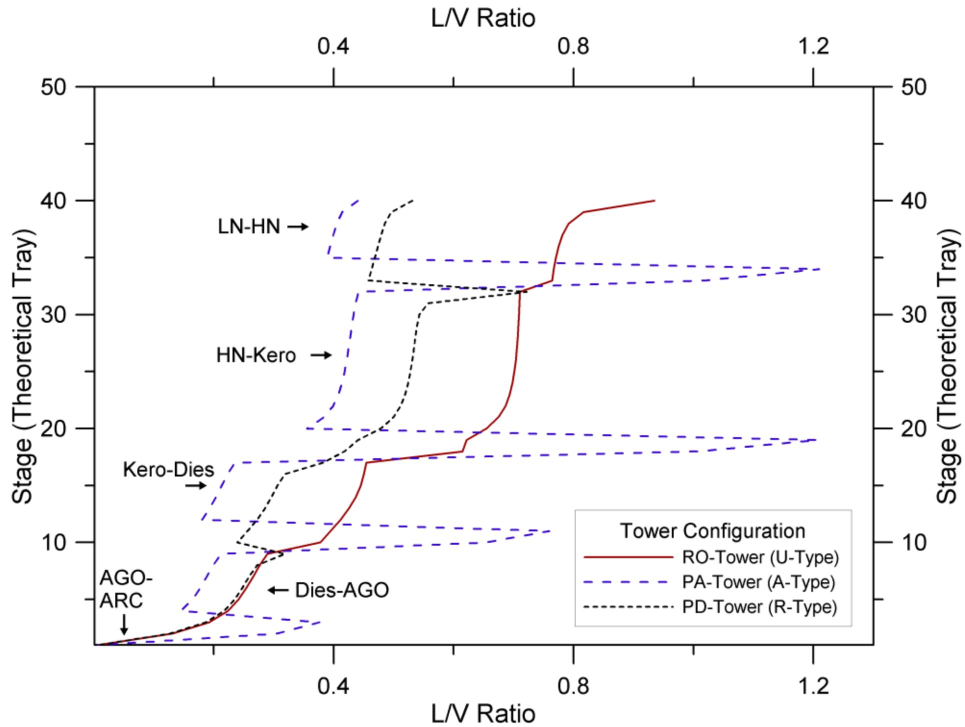

Figure 11 L/V Ratios versus stage for different configurations

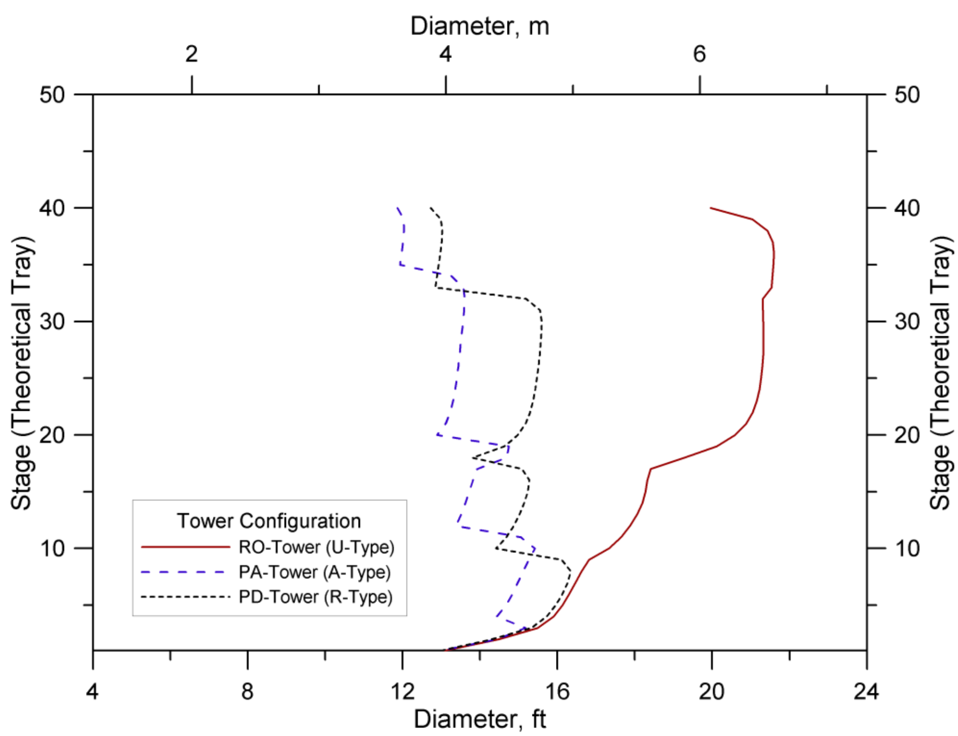

Figure 12 Diameter Comparison