Distillation Pilot Plant Design, Operating Parameters and Scale-up Considerations

Introduction

In spite of the fact that tremendous progress is being made in understanding the performance of both random and structured packings in distillation, it is a long way from being able to predict from first principles, the efficiency, capacity and pressure drop of a tower packing using thermodynamic and thermo-physical properties of the chemical system being distilled, as well as the physical parameters of the packing which aids the mass transfer. Those predictive methods that are available in the open literature have limited or poor accuracy if applied to a wide variety of chemical systems and tower packings.

The number of stages required for a given separation is obtained from the application of equilibrium thermodynamics. The actual number of stages obtained from a packed tower either in a laboratory, pilot plant, or an industrial plant is divided by the equilibrium stages predicted by vapor-liquid equilibrium thermodynamics to obtain an efficiency for the packed tower. Attempts have been made to generate semi-empirical correlations for packed tower efficiency from experimental data, and also generalized predictive models using the two-film theory of mass transfer. The mass transfer capability of a packing is typically expressed as HETP, HTU, \( K_{G,a} \) or \( K_{L,a} \), all of which are rate-controlled quantities, and they can all be converted from one to another.

Attempts to derive generalized predictive methods for the mass transfer efficiency of packings using the two-film theory and dimensionless groups, and for the pressure drop and capacity using mechanistic models, have met with varying degrees of success. Published results of these attempts are the works of Bolles and Fair (1979), Bravo et al. (1987), Fair and Bravo (1987), Stichhhair et al. (1989), Fair and Bravo (1990), to name a few. The models used in these predictive methods were checked against many sources of pilot plant data, especially those made by Fractionation Research, Inc. (FRI) and the Separation Research Program (SRP) of the University of Texas at Austin.

On the other hand, reliable semi-empirical or empirical correlations of efficiency, capacity and pressure drop specific to a packing supplier’s products can be found in their product bulletins, (e.g., Norton Chemical Process Products Corporation [NCPPC] 1987, 1992). These correlations are based on thermodynamic and physical properties of the systems, physical properties of the packings and numerous pilot plant tests and often operating data from industrial distillation columns. A very important need for ongoing pilot plant testing of tower packings in various distillation services arises because the existing predictive methods are either based on, or have been checked against only a limited data base i.e., limited number of chemical systems, system pressures (and temperatures) as well as packings. Thus pilot plant testing allows one to extend the database, which may suggest
the need to refine the predictive models whether they are empirical, semi-theoretical or theoretical.

Often times, pilot plant distillation tests are necessitated because the customer requests such tests. The customer is anxious to have these tests performed because they want to minimum design and installation risk when building a multimillion-dollar facility. These risks can arise because of the lack of good vapor-liquid equilibrium data, the likelihood of azeotrope formation or interactions between key components not well understood, uncertainties in new design goals like high product purities even for familiar chemical systems, need to evaluate a new operating mode, etc.

The authors will discuss, based upon their experience in mass transfer tower design, operation of Norton’s distillation pilot plants, and field feedback from the operation of commercial units, topics such as:

- Packing size to tower diameter ratio
- Distributor technology
- Bed depth
- Chemical system to be distilled
- Sampling techniques
- Reproducibility of results
- Operation pitfalls

**Norton Distillation Pilot Plants**

Norton Chemical Process Products Corporation (NCPPC) and its predecessor company has been operating a carbon steel distillation pilot plant for over 30 years at NCPPC’s Chamberlain Laboratories in Stow, Ohio. The internal diameter of the tower is 387 mm (15.25 in.) and it could accommodate beds up to 3050 mm (10 ft.) in depth. About seven years ago the height of this tower was raised so that it could accommodate a packed bed up to 6100 mm (20 ft.) in depth. This tower can operate at pressures in the range of 1.1 kPa (8 mm Hg. Abs.) to 170 kPa (10 psig). Most of the distillation data in the NCPPC data bank were collected using this carbon steel distillation column.

In 1992, NCPPC designed and built a new high-pressure distillation pilot plant. This tower and its ancillary equipment were fabricated from 316L stainless steel. This tower can be operated from high vacuum (0.133 kPa = 1 mm Hg. Abs.) to 2170 kPa (300 psig) at 177°C. It can be operated at pressures up to 2860 kPa (400 psig) at lower temperatures. This tower, like the carbon steel distillation tower has an internal diameter of 387 mm (15.25 in.). It can accommodate packed beds up to 7000 mm (23 ft.) in depth, resulting in a height-to-diameter ratio up to 18.
Both distillation pilot plants have similar flow schemes; they are located in a 12.2 m (40 ft.) tall high bay. The main difference is that the carbon steel distillation column sits atop a kettle reboiler, whereas the vapor produced in the stainless steel kettle reboiler enters the stainless steel distillation column through a 200 mm diameter side nozzle. A carbon steel skirt fastened to the floor supports the stainless steel column. Figure 1 shows the flow scheme of the stainless steel distillation tower, and Figure 2 is a scale drawing of the major pieces of equipment. Both columns can be operated at total reflux, or in the rectification mode at a LN ratio of less than 1. In addition, the high-pressure stainless steel tower has the capability to be modified as a center feed tower with beds up to 3050 mm (10 ft.) in the stripping as well as the rectification sections.

An important feature of the stainless steel tower is that it is provided with observation windows designed to withstand a pressure of 4236 kPa (600 psig) at 287°C. There are two pairs of windows in the vicinity of the reflux distributors and two pairs at the center feed location. One window of each pair is 100 mm in diameter used for illumination and the other window, which is perpendicular to the first, is 150 mm in diameter and is used for observation. The carbon steel distillation tower has three observation windows (150 mm diameter) in the vicinity of the reflux distributor. These observation windows permit the operator to observe the performance of the distributor, look for any entrainment of liquid in the vapor and the onset of flooding. These windows have proved to be extremely valuable tools to characterize the distillation performance of the tower packings and distributors that have been tested over the years.

In the design of both pilot plants particular attention has been paid to minimize the hold-up of liquid in the overhead condensate circuit, viz., condenser, condensate line, condensate tank and reflux line. Both pilot plants use vertical condensers with the vapor condensing in vertical tubes thus minimizing the hold-up of the overhead product. The reboilers of both pilot plants are just large enough to hold sufficient charge of liquid such that the increasing hold-up of liquid in the packing resulting from increasing boil-up does not drastically deplete the reboiler liquid of its light component. The carbon steel reboiler can hold up to 0.38 cubic meters (100 gallons) of liquid and the stainless steel reboiler can hold up to 0.57 cubic meters (150 gallons) of liquid.

The members of FRI and SRP have access to the test data generated in the respective test columns. FRI has the capability to run high vacuum to high-pressure systems and the SRP can run systems from high vacuum to 507 kPa (60 psig), but neither FRI nor SRP has the capability to run corrosive systems. FRI has 1213 mm (47.75 in.) and 2438 mm (8 ft.) I.D. column sections whereas the SRP tower has an I.D. of 429 mm (16.875 in.). As far as the authors are aware of, NCPPC’s stainless steel distillation pilot plant is the only one that is capable of testing all commercial size packings from high vacuum to high pressure in both non-corrosive and corrosive systems.
NORTON CHEMICAL PROCESS PRODUCTS CORPORATION
DISTILLATION PILOT PLANT

FIGURE 2
ELEVATION LOOKING FROM THE NORTH
We have tested all sixes of NCPPC random packings in one of the two pilot distillation units. The tower diameter-to-packing size ratio ranged from 5.5 to 26. This list includes all sizes of Intalox Metal Tower packings (IMTP packing), Pall rings, Hy-Pak packing and several other random packings. Furthermore, all sizes of NCPPC’s Intalox structured packings viz.; 1T, 2T, 3T, 4T and 5T, were also tested in these pilot distillation columns.

**Use Of Pilot Plant Data For Determining The Efficiency, Capacity And Pressure Drop Of A Tower Packing**

The aims of most pilot distillation tests of a packing with a particular chemical system are to determine:

- The mass transfer efficiency of the packing expressed as HETP or HTU
- The maximum hydraulic capacity and the maximum efficient capacity (MEC), i.e. the hydraulic capacity at which the efficiency starts to decline
- The pressure drop as a function of boil-up rate

![Diagram: RANDOM PACKING Height - Equivalent To A Theoretical Plate In Distillation Service, Strigle And Rukoneva (March, 1979)](image)
Figure 4: STRUCTURED PACKING - Height Equivalent To A Theoretical Plate In Distillation Service

Figure 3, which represents the typical HETP and AP vs. CS, data for random packings and large structured packings are from Strigle and Rukovena, (1979). Figure 4 represents similar curves for small structured packings. Here CS, is Souders and Brown (1934) entrainment parameter.

\[
C_s = \frac{G}{\sqrt{\rho_g / \sqrt{\rho - \rho_g}}} = V \sqrt{\frac{\rho_g}{\rho - \rho_g}} \quad \text{Entrainment Parameter} \quad (1)
\]

From the data of the type represented by Figure 3, the region B to C gives the design HETP and the point F gives the MEC. MEC represents the value of C, corresponding to the maximum rate at which the packing can be operated in distillation service while still maintaining the typical HETP as represented by the B to C portion of the HETP curve.
Figure 5: #25 INTALOX METAL TOWER PACKING SYSTEM - System: Iso-octane / Toluene, 98.7 kPa Abs [740 mm Hg Abs] data by Norton
Figure 6: #50 INTALOX METAL TOWER PACKING SYSTEM - System: Iso-octane / Toluene, 98.7 kPa Abs [740 mm Hg Abs] data by Norton
Figure 7: INTALOX STRUCTURED PACKING IT - System: Iso-octane / Toluene, 13.3 kPa Abs [100 mm Hg Abs] data by Norton
Figure 8: INTALOX STRUCTURED PACKING 4T - System: Iso-octane / Toluene, 13.3 kPa Abs [100 mm Hg Abs] data by Norton
From the type of data as represented by Figure 4, i.e., for small structured packings, the MEC is determined by the C value at which the slope of AP vs. C, curve approaches infinity. The design HETP is taken at 90% of the MEC. Figures 5, 6, 7 and 8 show actual test data on No. 25 IMTP packing and No. 50 IMTP packing, Intalox Structured Packing 1T and Intalox Structured Packing 4T, respectively.

For most binary systems that we test in the pilot distillation columns, the number of stages generated in the packing is calculated using the method of Neretnieks et al. (1969). This method applies a coordinate transformation to the McCabe-Thiele method to account for the difference in the molal heats of vaporization between the two components. For multi-component systems, the stages are calculated using commercially available process simulators.

The MEC point is confirmed by the heat balance on the distillation column. When the HETP starts to increase (decreasing efficiency) because of entrainment, this entrainment is carried into the condenser. This entrainment then manifests in the heat balance around the condenser as more heat being removed from the overhead based on the condensed vapor rate, than was put into the re-boiler.

The pressure drop across the packed bed is measured with the help of pressure taps above and below the packed bed and pressure transducers.

**Factors To Be Considered In The Design And Operation Of A Distillation Pilot Plant**

In operating an existing pilot plant distillation column, there are three fundamental issues involved:

a. Chemical test system  
b. Tower packing  
c. Liquid and or gas distributors

Typically, in a particular pilot test the performance data on two out of these three items are known fairly well; it is the purpose of the test to get information on the performance of the third item in the presence of the other two.

But in designing a new pilot distillation column one needs to decide ahead of time the type of chemical systems, whether corrosive or non-corrosive, high vacuum, atmospheric, or high pressure system that will be distilled in the column. As discussed earlier, the size and type of the packings and distributors to be tested will also have to be considered. From an economic standpoint, the most important consideration is the diameter of the pilot distillation column.
A. Tower Diameter To Packing - Size Ratio

Most of the early laboratory distillation data were taken in small columns, say 150 mm (6 in.) or less. Only very small random packings, viz., 3 to 12 mm (0.12-0.5 in.) in size could be tested in such columns. There were several reasons for this. As the diameter of the pilot plant distillation column increases, in addition to the increase in installed cost, the cost of operating utilities, viz., reboiler steam and condenser cooling water increase proportional to the square of the tower diameter. Thus there is strong economic incentive for keeping the tower diameter as small as possible without affecting the quality of the test data.

One consideration was the rule of thumb that the test tower diameter should be at least 10 times the size of the packing. The rationale behind this rule is that if larger packings were used, the wall area surrounding the packed bed would be a significant fraction of the packing area, and as such the column wall would provide a significant portion of the mass transfer area. It follows, based on this reasoning that when scaling up such data to large towers some derating would be necessary.

On the other hand, it can be argued that in a small tower, the gap between a bed of large packings and the tower wall can cause partial short-circuiting of liquid and vapor through these gaps. For structured packings, wall wipers minimize this problem. In large commercial towers the effect of such gaps will have negligible effect on packed bed hydraulics.

Most of the commercial size random packings fall in the size range of 15 mm to 90 mm (0.6-3.5 in.), and the structured packings has crimp heights in the range of 6 mm to 30 mm (0.25-1.2 in.). But the majority of random packings sold commercially fall in the size range of 25 to 70 mm (1-2.8 in.), while the majority of commercially sold structured packings have crimp heights in the range of 8 mm to 12 mm (0.3-0.8 in.). With the 387 mm I.D. pilot distillation columns that NCPPC operates, it was found possible to test random packings in the size range of 15 mm to 70 mm (0.6-2.8 in.); the column I.D. to packing size ratio ranged from 26 to 5.5. In the case of the structured packings that were tested in these towers, the column I.D. to crimp height ratio ranged from 13 to 65. Based on experience with commercial installations, the test data taken in a 387 mm I.D. column gives reliable design data for commercial size columns. As mentioned earlier, the FRI columns have relatively large diameters, viz., 1213 mm (47.75 in.) and 2438 mm (96in.), probably because they were originally designed for testing trays. But the SRP columns which were built in 1986 have 429 mm (16.875 in.) I.D., because they were designed primarily for testing packings. Similarly another distillation pilot column operated by the Delft University of Technology in the Netherlands has an I.D. of 450 mm (17.72 in.) (Olujic et al., 1992). Thus, a distillation pilot column of approximately 400 mm...
(16 in.) I.D. gives reliable test data on random and structured packings. This type of test data along with reliable distribution technology can be used, without any scale-up factor, to design commercial distillation columns.

B. Distribution Technology

Factors to be considered in selecting liquid distributors for a distillation test tower are:

- Turndown ratio and height of the distributor
- The number and size of distribution points (orifices) per unit tower cross-sectional area
- The liquid flow variation allowed between distribution points
- The layout of the liquid distributor points over the tower cross-sectional area

It is common practice, when testing a packing, to cover the complete operating range of the packing. In the authors’ experience, the typical turndown ratio is 5:1. And, it is not uncommon to have a 7:1 turndown ratio. Several types of liquid distributors are used for distillation tests. Except for the notched weir-trough distributor (which happens to have high turn-down ratio), spray distributor (which is seldom used in distillation), most of the distillation distributors fall into one of the following three categories.

- Orifice-pipe arm distributors
- Orifice-pan distributors
- Orifice-trough distributors

Let us first consider the design of orifice-plate and orifice-trough distributors. Both of these types of distributors are open at the top. In the orifice pan distributor, the gas flows through specially designed risers as well as the area between the pan and the tower wall. The rest of the pan area is available for locating liquid orifices. In the orifice-trough distributor, the liquid is held in specially designed troughs with liquid orifices at the bottom and/or on the sides of the troughs; the rest of the tower cross-sectional is available for gas flow.

For a given orifice size, the flow rate through the orifice is approximately proportional to the square root of the liquid head, when the orifice is running full of liquid. Therefore, for a given set of orifices at a fixed elevation, the required head of liquid above the orifices is proportional to the square of the liquid flow rate. Thus a $2:1$ turndown ratio in flow requires a $4:1$ ratio of liquid head. Typically the minimum liquid head required for predictable flow of liquid through the orifice is about 50 mm (2 in.). Thus the liquid head required at maximum flow rate for $2:1$ turndown is 200 mm (8 in.). For $5:1$ turndown the maximum is 1250 mm (50 in.), and for $7:1$ turndown the maximum head
required is 2450 mm (8 ft.). It follows that, unless over 2.5 m (8 ft.) of column height can be reserved for liquid distributor, one must resort to using a distributor with multiple levels of orifices or use more than one single-level orifice distributor, each with a different orifice size. The design features of many of these types of distributors are proprietary.

The pipe-arm distributors depend, for their performance, on the liquid head prevailing upstream of the orifices; this pressure is generated usually by a liquid feed pump. The turndown capability of the pipe-arm distributors are only limited by the capacity of the feed pump and the maximum allowable velocity of liquid through the orifices above which formation of liquid spray might cause entrainment. The biggest drawback of this type of distributor is that the flow variation from orifice to orifice can be excessive, especially at high flow rates due to variability of the size and shape of the orifices and the pressure drop through the pipe arms. Therefore, orifice-pan and orifice-through distributors are generally preferred for both pilot plant distillation columns and industrial distillation columns.

The number of liquid distribution points required for unit tower cross-sectional area is a function of the type and size of the packing. Based on the authors’ experience, the following general statements can be made:

- Large random packings require fewer pour points than smaller random packings.
- Large structured packings require fewer pour points than medium sized structured packings.
- Small structured packings have better liquid spreading characteristics than larger structured packings.
- Except for small random packings, most packings will operate well with pour point densities of between 40 points/m² (4/ft²) and 60 points/m² (6/ft²). Even small random packings of commercial interest perform well with 100 points/m².
- The smallest size orifice used is 2-3 mm in diameter; this small orifice can only be used with clean systems.
- Sufficient liquid head should be allowed to limit the individual orifice flow variation to ± 5% of the average flow rate.
- The layout of liquid distributor orifices over the tower cross-sectional area is based on the method of Moore and Rukovena (1986).
C. Bed Depth

Table 1: Intalox Structured Packing Performance

<table>
<thead>
<tr>
<th>LIQUID DISTRIBUTOR</th>
<th>NORTON: INTALOX STRUCTURED PKG 1T</th>
<th>HUKILL: INTALOX STRUCTURED PKG 2T</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTS/m²</td>
<td>THEORETICAL PLATES AND HETP</td>
<td>THEORETICAL PLATES AND HETP</td>
</tr>
<tr>
<td></td>
<td>BED DEPTH, mm (ft)</td>
<td>BED DEPTH, mm (ft)</td>
</tr>
<tr>
<td></td>
<td>theoretical Plates</td>
<td>HETP, mm</td>
</tr>
<tr>
<td></td>
<td>2,908 (9.5)</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>5,828 (19.1)</td>
<td>10.6</td>
</tr>
<tr>
<td></td>
<td>11,532 (37.8)</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Several considerations go into choosing the maximum allowable depth of a packed bed. Maximum number of theoretical stages generated in a bed e.g., 15 theoretical stages per bed is a rule of thumb used often. But as Table I shows we have observed packed beds of Intalox Structured Packing 1T generating over 21 theoretical stages in a single bed, irrespective of the pour point density. Table I also shows that a single bed of Intalox Structured Packing 2T can generate as many as 32 stages in a single bed.

Height-to-diameter ratio of the bed again, as can be seen from Table I, the authors have observed that a bed of Intalox structured packing can operate well with a height-to-diameter ratio of up to 15.

Another consideration is the mechanical strength of the packing and the support system for a tall bed. A packed bed depth chosen based on the two criteria listed above can be supported without any problem.
D. Chemical Systems To Be Distilled

A large number of pilot plant tests are performed during the various stages in the development of a new packing. Since the primary purpose of these tests is to compare the performance of the new packing with other packings, all tests are performed with one or a few chemical systems. For example, Zuiderweg (Circa 1966) lists a number of test mixtures that can be used at atmospheric, vacuum and pressure distillation. FBI typically uses the cyclohexane-heptane system at 34.5 kPa (260 mm Hg Abs), atmospheric pressure and 165 kPa (24 psia), the p-xylene/o-xylene system at 13.3 kPa (100 mm Hg Abs) and lower, and the i-butane/n-butane system at high pressures ranging from 689 kPa (100 psia) to 2758 kPa (400 psia). The SRP typically uses the test system cyclohexane/n-heptane at 33.3 kPa (250mm Hg Abs), atmospheric pressure, 165 kPa (24 psia) and 413 kPa (60 psia).

Historically, NCPPC has used the iso-octane/toluene system at atmospheric pressure and 13.3 kPa (100 mm Hg Abs) as the standard test system. We also have used the cyclohexane-heptane system and p-xylene/o-xylene system as standard test systems.

In the carbon steel tower, NCPPC has tested our packings with numerous other chemical systems, e.g., methanol/water, cyclohexanone/cyclohexanol, acetone/water, water/MEG, to name a few. We also have tested numerous proprietary systems for our customers over the years. Using the data generated from our test columns, as well as commercial installations, NCPPC has developed, efficiency, capacity and pressure drop correlations, which have been used to design world-class high vacuum to high-pressure distillation columns using NCPPC packings.

In the future NCPPC will be adding, to its data bank, test data on high pressure and corrosive systems taken in our high-pressure stainless steel distillation column.

E. Sampling Techniques

Generation of HETP data from distillation tests requires drawing samples from the system after steady state has been attained. For example, during a distillation test in the rectification mode, liquid samples are drawn from the overhead vapor condensate, from below the packing and from the reboiler. The overhead sample is collected from the discharge side of the reflux pump. The sample from under the packing is collected using a trough type sampler in the shape of a cross; the liquid leaves the sampler from the center and is conducted through tubing to the outside. These samples are chilled, if necessary, to avoid loss due to vaporization and consequent change in composition. At a given boil-up rate, the onset of steady state is monitored by drawing samples periodically, say every 1/2 hour, and analyzing the samples. For most binary organic systems, a gas chromatograph is...
the most convenient analytical tool. The difference between the compositions of the light component in the overhead sample minus that in the packing sample increases gradually until it reaches an asymptotic value at steady state. During the run, three consecutive samples are taken at half hour intervals. Typically, for a good run at steady state HETP values calculated using the three samples differ from one another by no more than 8 mm (0.3 in.). For example, in Figure 5, for every run (i.e., Cs) three HETP values and delta P measurements were obtained. It can be seen that for the majority of runs the three measurements coincide with one another. The time required to attain steady state, after changing the boil-up rate, is typically about two hours for common organic systems with relative volatilities above -1.1. But systems with relative volatility approaching 1, e.g., isotopes, it can take from 16 to 24 hours for the attainment of steady state composition profile in the packed bed. The reboiler sample, together with the sample drawn from under the packing, is used to calculate the number of stages generated in the reboiler – which is usually around 1; this procedure is used as a check on the accuracy of the sample drawn from under the packed bed.

F. Reproducibility Of Test Results

Factors that affect the reproducibility of test results for a given packing, without considering the manufacturing tolerance of the packing are numerous.

Method of packing the distillation column. For structured packings, care should be taken to see that the wall wipers properly engage the tower wall so that bypassing of vapor and liquid through the gap between the packing and the tower wall are minimized, if not eliminated. It is important that consecutive layers of structured packing are rotated by a fixed angle, usually 70” with respect to each other, so that the seams of segmental bundles do not line up (for a 387 mm (15.25 in.) I.D. test tower each layer is made as a single piece). We make sure that no gap is allowed to exist between the packing and manways. A plug contoured in the shape of the tower wall is pressed against the packing. We have noticed that, in the absence of this plug, short-circuiting of liquid and vapor can result in poor packing efficiency.

Analysis of samples - In a typical distillation test in which gas chromatography is used for analyzing the samples, it is important that standards are run every day. It is necessary to make a sufficient number of standards to cover the anticipated range of composition bracketing that of the overhead sample and the re-boiler sample. In a binary mixture, for example, the response factors of the two components can vary over the range composition. The response factors can be drastically different when the composition approaches pure light component and pure heavy component compared to those of a 50-50 mixture.
Insulation of the tower walls- In both our distillation pilot plant, (150 mm (6 in.) thick fiberglass blanket insulation with aluminum wrap is used to cover the re-boiler and the tower wall to minimize condensation of the internal vapor traffic at the tower wall; this condensation would otherwise affect the internal reflux ratio. We try to limit the heat loss to about one percent of the heat input to the reboiler.

Accurate and reproducible pressure drop measurement requires careful design of pressure taps and lines leading to the pressure transducers. It is important to make sure that any vapor that condenses in the lines flows back to the tower without affecting the pressure measurement. The pressure taps are designed so that the opening faces downwards to prevent liquid from entering the tap. A baffle is provided in the opening to prevent vapor from impinging on the opening. This baffle ensures that only static pressure is measured. Typically 12 mm (0.5 in.) diameter tubing, which continuously pitches from the transducer to the pressure tap, assures that any vapor condensing in the line runs back to the tower.

The authors have found that it is possible to obtain reproducible HETP data on the same system-packing combination, after repacking the tower and recharging the system, with variation not exceeding 15 mm (0.6 in.).
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Nomenclature

Cs = Entrainment Parameter, Eq. 1, Souders and Brown, m/s
G = Gas Rate, kg/m²s
V = Gas Velocity, m/s
p_G = Gas Density, kg/m³
p_L = Liquid Density, kg/m

Subscripts

G = Gas
L = Liquid
s = Souders and Brown