TRAY CAPACITY LIMITATIONS AT LOW SURFACE TENSION

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Tray vapor capacity correlations typically do not include a surface tension physical property parameter. Low liquid surface tensions that exist on a typical high pressure distillation tray can lead to tiny droplet sizes in the vapor space, high liquid entrainment and limited vapor capacity. Several authors have examined surface tension as a capacity limiting parameter in the past, but some of today's leading vapor capacity correlations have omitted this important physical property. This paper will examine very low surface tension data as well as a wide range of surface tension capacity data and then discuss a new tray vapor capacity correlation that uses surface tension as the primary correlating parameter. The intent of this paper is to show that tray designs of very high pressure trayed distillation towers, such as Demethanizers and Deethanizers, can be made without the need for "system factors" with this new correlation. It is the author's opinion that any applied "system factor" should be used strictly for those tray applications that are limited in capacity due to foaming and not be used as a "fudge factor" to account for capacity correlation deficiencies.

Data Evaluation

Fractionation Research Inc. (FRI) has examined sieve tray data for several decades starting in 1955(1). The work in this paper utilizes this data extensively, especially the data at very low surface tensions. The FRI data chosen to be evaluated was efficiency data, near the flood point, all taken at total reflux conditions. In total, 78 sets (not single data points) of efficiency data from FRI were examined. The examined data fell into the following ranges;

Pressure	0.193 – 500	psia
Surface Tension	0.23 – 26.2	dynes/cm
Tray Spacing	12 - 36	inches
Weir Height	0 - 4	inches
Hole Diameter	0.125 – 1.0	inches
% Open Area	4.97 – 19.5	
Weir Loading	0.44 – 12.0	gpm/inch

In addition to this very valuable data from FRI, we at Sulzer have extensive air-water simulator data for ½" sieve trays. With this simulator data, the range of surface tension data is expanded to 67 dynes/cm. Based on the author's personal experience, the most important parameter that helps determine any type tray capacity is surface tension. The value of the surface tension determines the relative droplet size above the tray deck and the subsequent ease that those droplets can be entrained resulting in jet flooding. The lower the surface tension, the smaller the droplet size and the lower the value of the vapor C-factor it takes to entrain massive numbers of those droplets to the tray above. Of secondary importance is weir loading, tray spacing, and opening size. The C-factor used here is derived from the work of Souders and Brown(2) as described in Perry's Chemical Engineering Handbook, 8th Edition page 14-36.

To ensure that the data sets that were evaluated were not influenced by downcomer limitations or were not operating in the Spray Regime, all data points were eliminated that had downcomer velocities exceeding 70% of Equation 1(3) and spray factors that were less than 2.78, based on Equation 2(4). This approach ensured that the onset of flooding (or reduction in tray efficiency) was caused exclusively by high entrainment or jet flooding.

Entrainment flooding can actually be generated differently depending on the Flow Regime on the tray. Most industry experts will agree that there are three main flow regimes on a tray. There is the very high liquid load regime called the Emulsion Regime where the vapor jets are sheared off by the high velocity liquid flowing across the tray. There is the Froth Regime (some people may refer to this regime as the Bubbly Regime) where the vapor jets flow through the liquid phase and form a froth above the tray.

This froth can be quite violent with liquid droplets flying above a defined the frothy layer. Then there is the Spray Regime where there is no defined (or visible) froth and the volume above the tray is vapor continuous with droplets "dancing" around in that space. The Spray Regime, as defined here, needs to be avoided because tray performance is very poor due to high entrainment and lack of contact time between the liquid and vapor. Jet Flood, and Jet Flood Equations provided here, apply exclusively to the Froth and Emulsion Flow Regimes. The Spray Regime has no flooding correlation, only a prediction of when it may occur (as defined in reference 4) and should be avoided at all times.

$$DCVel = 0.1747 * Ln_e(\rho_L - \rho_V)) - 0.2536 \qquad \text{Eq. 1}$$

$$\text{Spray Factor} = H_{CL} * \rho_L^{0.5} / (0.3048\ Dp\ U_H\ \rho_V^{0.5}) \qquad \text{Eq. 2}$$

Where,

DCVel = Maximum Downcomer Velocity, ft/sec
H_{CL} = Clear Liquid Height, inches
Dp = Hole Diameter, inches
U_H = Vapor Hole Velocity, ft/sec
ρ_V = Vapor Density, lb/ft^3
ρ_L = Liquid Density, lb/ft^3

It needs to be noted that the jet flood (or entrainment flood) described here only applies to the froth flow regime and the emulsion flow regime on a tray. The spray regime cannot be described by conventional entrainment correlations and has a different flooding mechanism altogether(5). In addition, the pure component surface tension of isobutane and normal butane was examined to ensure the reported FRI surface tension values were correct, which they were.

To look exclusively at the surface tension effect, the examined data sets all had the same 48" tower diameter, 24" tray spacing, 2" outlet weir height, ½" hole diameter, 16 gauge tray thickness (0.063"), and 1-Pass flow pattern.

A single set of tray efficiency data that was examined was a series of FRI Total Reflux (TR) data vapor and liquid load points for a particular tray design and constant (steady state) operating conditions. For example, efficiency data set series #14.1 from 1957, will be examined here. FRI data run numbers 1406 to 1414 were carefully reviewed, as plotted in Figure 1. As noted in this figure, data point #1409 was chosen to represent the maximum useful capacity data point of this set because it exhibited the highest efficiency just before a reduction in significant tray efficiency is noticed and flooding occurs. As can be seen, there is some residual capacity before the tray becomes fully flooded when choosing this point as a maximum useful capacity point. This extra capacity is viewed by the author as a safety factor. At vapor loads above the maximum useful capacity, entrainment will have some negative influence on tray efficiency but the tray will still have extra capacity before full jet flood.

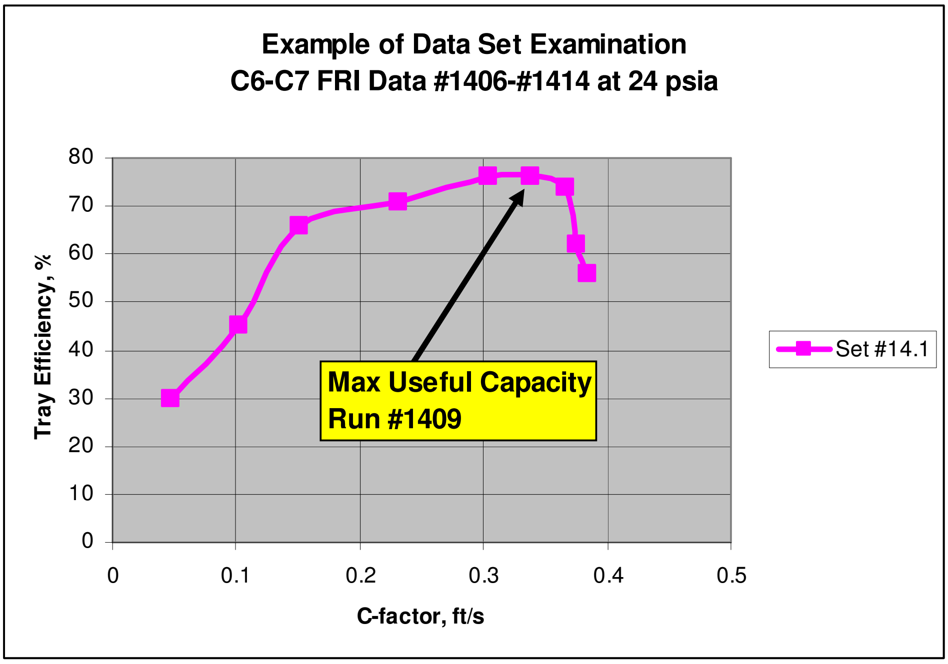

Figure 1 – Example of Data Set Examination

Correlation Development

A summary of all the data points chosen to represent maximum useful capacity over the full spectrum of surface tensions available at 24" tray spacing, 2" outlet weir height and ½" hole diameter is shown in Table 1.

Table 1 – Specific Surface Tension Data

FRI Run Number	Surf Ten dynes/cm	C-factor ft/s	Weir Load gpm/in
8108	0.26	0.207	6.46
8109	0.23	0.190	5.94
8092	1.02	0.268	7.11
8077	2.29	0.304	6.50
8067	5.16	0.324	4.85
1324	14.02	0.343	4.15
1409	14.5	0.338	3.71
4217	18.52	0.332	2.66
4218	19.36	0.319	2.46
Sulzer Data	67	0.331	6.04

The C-factor as initially described above is defined in Equation 3 which is based on the Free Area of the tray. Free Area is the tower cross-sectional area above the tray deck available for vapor expansion. Basically it is the Tower Area minus the downcomer bottom area. However, experience has shown that full credit may not be taken for the space above large downcomers. Therefore, a modified Free Area definition was devised to limit the potential for vapor expansion above large downcomers such that the Free Area is limited to be 1.15 times the Tray Active Area. Free Area should not be confused with tray Active Area which is defined as the Tower Area minus the downcomer bottom area and minus the downcomer top area.

$$\text{C-factor} = (Q_V/Af)\,(\rho_V/(\rho_L - \rho_V))^{0.5} \qquad \text{Eq. 3}$$

where,

Q_V = volume of vapor flowing through the tray, ft^3/sec
Af = Free Area as defined above, ft^2
ρ_V = Vapor Density, lb/ft^3
ρ_L = Liquid Density, lb/ft^3

Air-water simulator data from Sulzer(6) at 10% liquid entrainment shows the affect of weir loading on the jet flood capacity C-factor, see Figure 2. If you ignore the spray regime points to the left of the figure, as a different flooding mechanism, then the remaining points have a slope of -0.0016. Therefore, one can "correct" the C-factor in Table 1 and eliminate the weir loading affect on Jet Flood. This results in a term called the C_f' or zero weir load C-factor. C_f' is equal to C-factor plus 0.0016 times the Weir Loading.

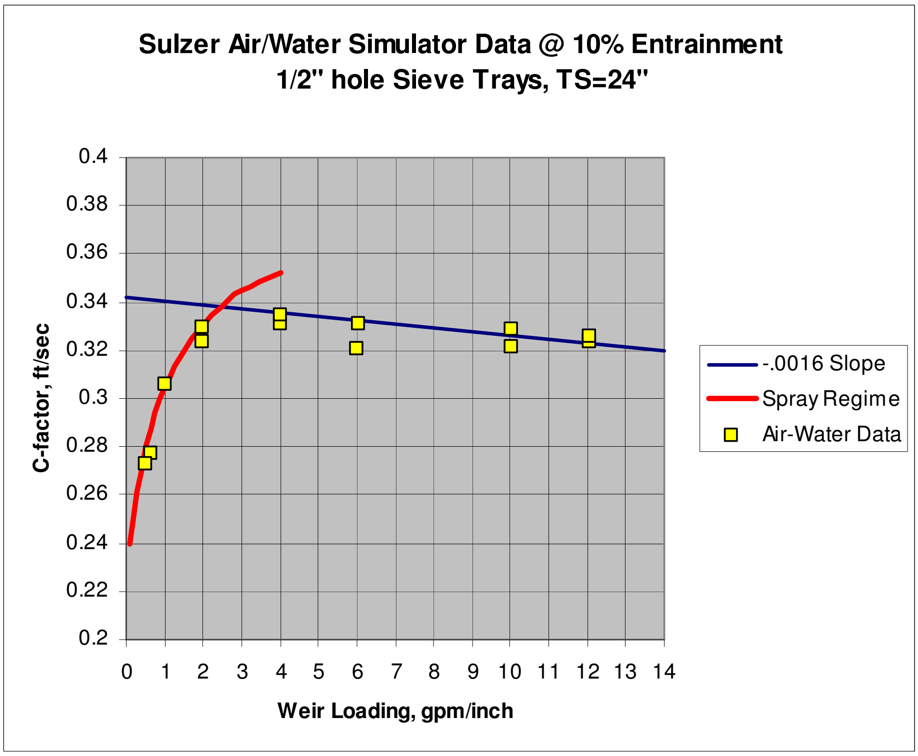

Figure 2 – Effect of Weir Loading on Sieve Tray Capacity

When one plots the C_f' of the Table 1 data points against Surface Tension, one is able to generate Figure 3.

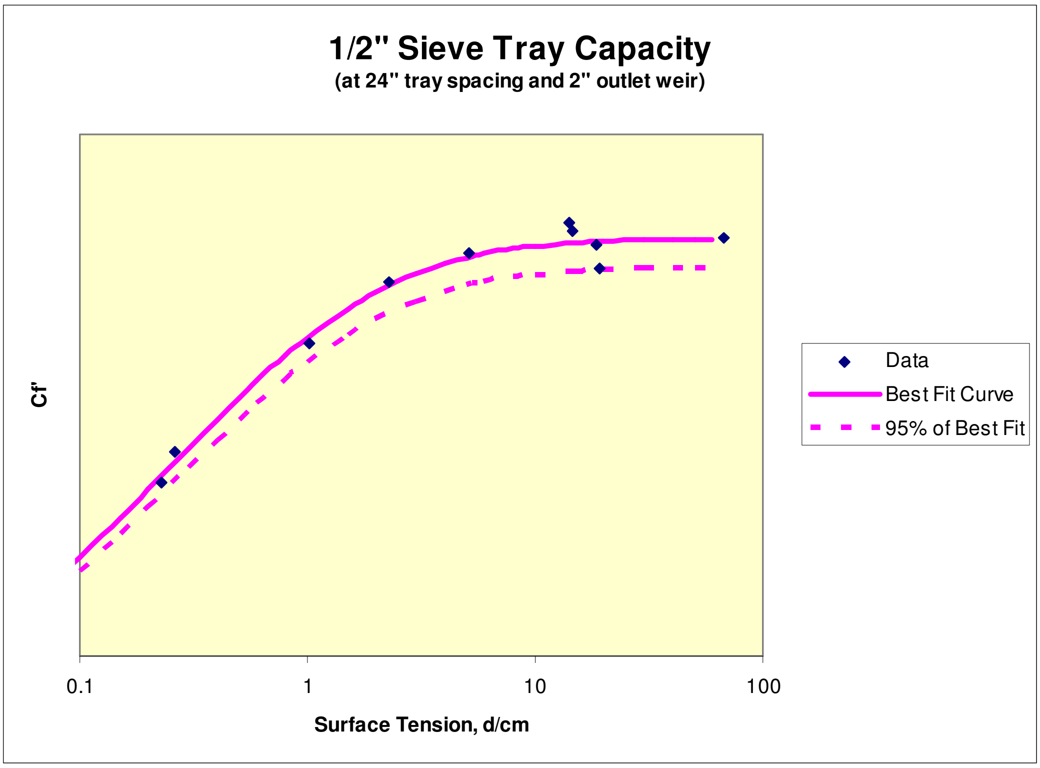

Figure 3 – Sieve Cf' at Zero Weir Loading

To get 100% confidence that all maximum capacity data points are captured by the new capacity correlation, a 95% of best fit line through the data is shown in Figure 3. This 95% will be labeled as F'. The 95% line provides a 5% safety margin which ensures that towers designed near their maximum capacity will have some additional operating flexibility.

Since all the data in Figure 3 is based on 24" tray spacings, data at other tray spacings can be simply added as multipliers with a power function. FRI data was provided at 12", 24" and 36" tray spacings. For the 12" tray spacing data, the power on the tray spacing multiplier was found to be 0.52. For the 36" tray spacing data, the power on the tray spacing multiplier was found to be 0.44. Table 2 shows the data used to determine the power on the tray spacing ratio. All this data had 2" weir heights and ½" hole diameters. An interpolation between these two points will result in the power becoming a linear function instead of the more popular constant value of 0.5.

Table 2 – Sieve Tray Data to determine Tray Spacing adjustment

FRI Run	Pressure	TS	C-factor	Weir Loading
Number	psia	In	ft/sec	gpm/in
2621	4	12	0.227736	1.33
2503	14.7	36	0.394129	3.55
2459	24	36	0.397359	4.87
2610	24	12	0.225512	2.58
2644	24	12	0.230451	2.67
9631	165	12	0.238886	3.17
8325	300	36	0.356299	10.02
9640	300	12	0.220305	4.12

For the hole diameter, another simple multiplier with a power function can be applied. Here specific FRI data using hole diameter data needed to be identified. This hole diameter data is the FRI data points shown in Table 3. For this data, taken at 24 psia, the weir loadings were all between a relatively small range of 3.5 and 4.4 gpm/inch. The best fit power on the hole diameter multiplier was found to be quite small, but necessary, at 0.06.

Table 3 – Hole Diameter Data Points

FRI Data Run No.	Hole Diameter, Inches	Predicted Max Cf With No Power	Predicted Max Cf With 0.06 Power	Actual Cf Ft/sec
2830	0.125	0.3305	0.3592	0.3610
1452	0.1875	0.3315	0.3516	0.3506
1409	0.5	0.3318	0.3318	0.3382
1491	1.0	0.3318	0.3183	0.3120

Outlet weir height and open area fraction had no effect on tray capacity. There is extensive FRI data at 24 psia with weir heights that range from 0 inches to 4 inches and open areas that range from 8 to 20%. As can be seen from Table 4 and Figure 4, there is no effect of Outlet Weir height on maximum tray capacity for the C6-C7 system at 24 psia and ½" hole diameters. Figure 5, for the same data, shows only a slight effect of open area on tray capacity. At the lowest open area, the difference in C-factor is only 4% less than the average. This is not large enough to warrant a modification to the resulting capacity correlation in the author's opinion.

Table 4 – Weir Height effect on Tray Capacity

FRI Run	Weir Height, in	Cf, ft/s	Fraction Open Area
551	0	0.3417	0.1946
583	0	0.3232	0.1946
3628	0	0.3365	0.1373
1324	2	0.3425	0.1373
1409	2	0.3383	0.1373
1419	2	0.3217	0.0832
5715	2	0.3171	0.0832
1808	4	0.3218	0.0832
3667	4	0.3386	0.1373

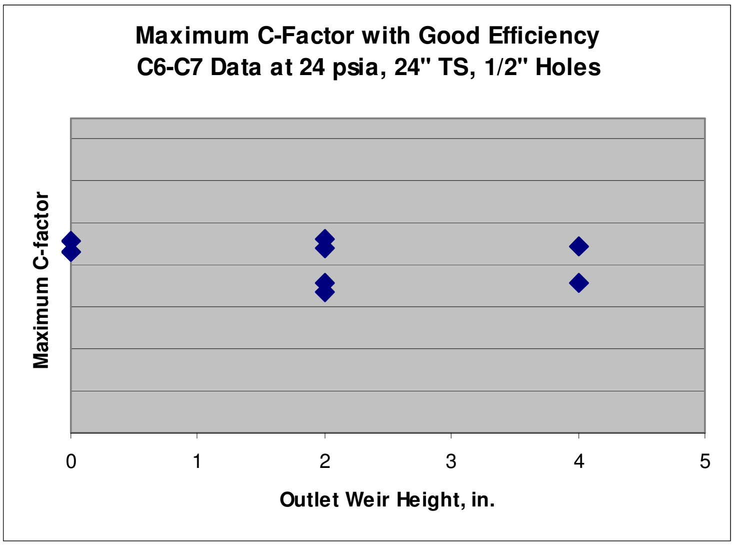

Figure 4 - Weir Height effect on Tray Capacity

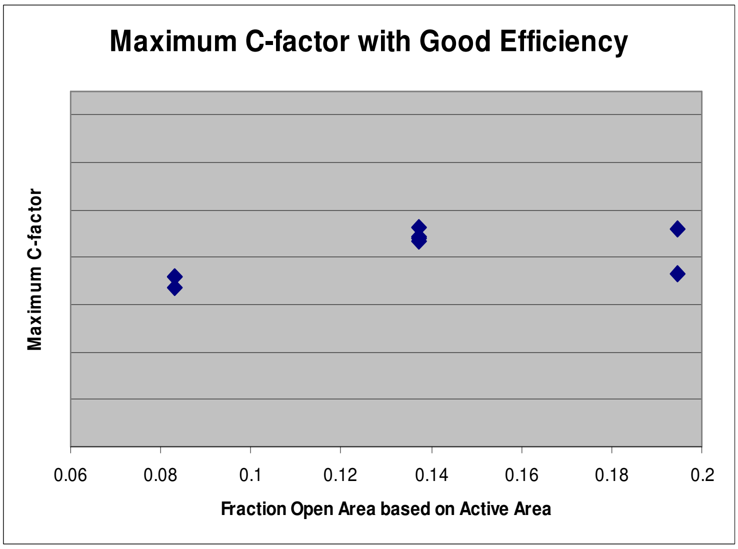

Figure 5 – Open Area effect on Tray Capacity

The final maximum useful capacity equation can be compared to other common tray capacity correlations. One of the most common is Glitsch "Equation 13"(7). This equation does not have a surface tension term at all. Another correlation is by Fair(8) which does contain a surface tension effect. The Kister-Haas(9) equation is a widely accepted sieve tray capacity correlation. FRI also has a correlation for jet flood capacity of sieve trays(10). The FRI Correlation results shown here were generated by the correlation depicted in Topical Report 112 and is shown with permission from FRI. The correlation from Topical report 112 is not the latest correlation capacity correlation developed by FRI for sieve trays and we were not given permission to exhibit the results from that correlation.

Each of these correlation's predicted results, for the FRI data run numbers shown in Table 1,are shown in Figure 6. This chart shows % Jet Flood as a function of surface tension for these data points, all of which should have a value of 85% Jet Flood. Only the correlation presented in this paper shows agreement with the data over the entire surface tension range. The FRI Correlation is excellent above surface tension values of 5.0 dynes/cm. The Kister-Haas Correlation mirrors the FRI correlation except that the predicted % Jet Flood numbers are 20 to 30% higher. The Kister-Haas correlation was not recommended for surface tension values less than 5 dynes/cm. The Glitsch Correlation and the Fair

Correlation both give <u>excessively</u> conservative predictions for the % Jet flood at low surface tensions and should not be considered for such applications.

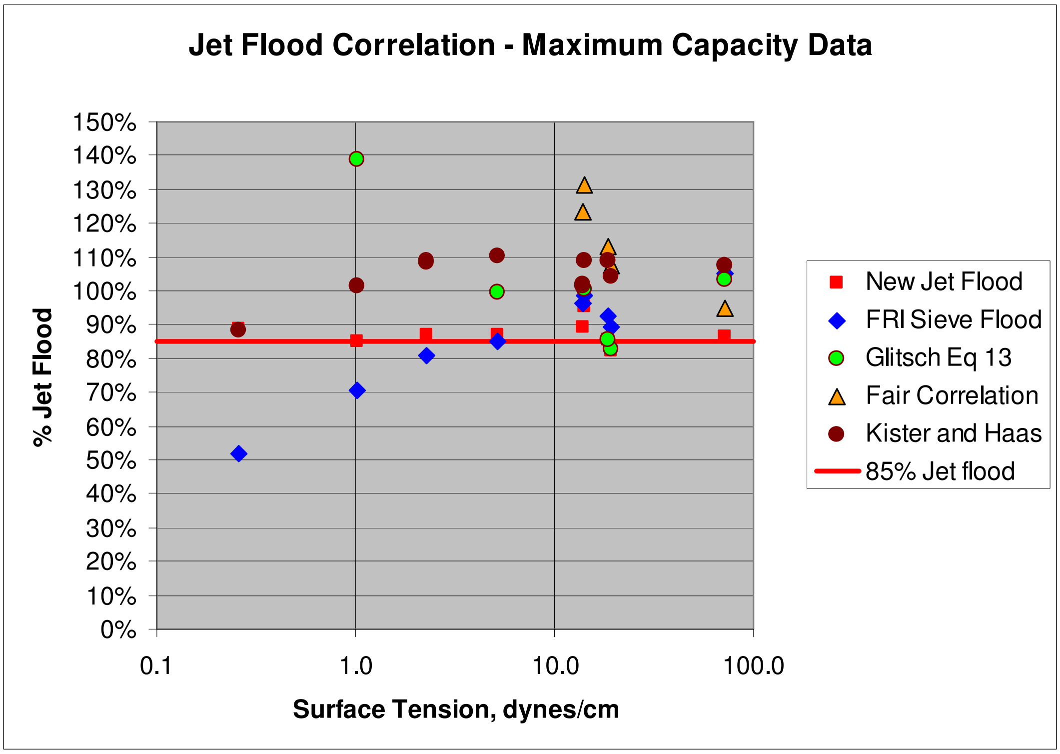

Figure 6 – Comparison of Various Capacity Correlations

System Factor

Literature has indicated that "With certain systems, traditional flooding equations consistently give optimistic predictions."(11) One of the areas where tradition has dictated the need for a system factor has been high pressure hydrocarbon applications (e.g. Demethanizers, Deethanizers and even Depropanizers). Derating factors for such systems, found in Table 14-9 of reference 11, show values of 0.8 to 0.85 for these applications. This difference in capacity can be readily seen in Figure 6 between the new correlation given here and the optimistic FRI capacity correlation (for example) at surface tensions between 1 and 2 dynes/cm. No derating factor is needed with the new sieve tray capacity correlation.

Other Tray Types

The new correlation development philosophy given here for sieve trays is also applicable to other fixed opening devices such as Sulzer's V-grid family of trays (SVG, MVG and MMVG) as well as Sulzer's movable (float) valve tray family. All have had their predicted maximum capacity correlated in a similar manner against surface tension, especially at high pressure(12).

Conclusions

A new Jet Flood correlation for Sieve trays has been developed. This correlation fits the data extremely well especially for low surface tension (high pressure) applications. System factors need not be applied to this correlation unless the system is TRULY foaming. Similar correlations for all other Sulzer tray types have been developed and are currently in use in SulCol(13).

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