

Column hydraulics: system limit/ultimate capacity

Carl. W. Fitz Jr., John G. Kunesh*

Fractionation Research Inc., P.O. Box 2108, Stillwater, OK 74076, USA

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Abstract

The concept of system limit or ultimate capacity has been around for over 40 years. During the period 1959–1961 Tek [F.R.I. Topical Report 21, Special Collections Section, Oklahoma State University Library, 1959; F.R.I. Topical Report 25, Special Collections Section, Oklahoma State University Library, 1961] combined the entrainment flood approach of Souders and Brown [I&EC 26 (1) (1934) 98] with the drop stability work of Hinze [Appl. Sci. Res. A1 (1949) 273; AIChE J. 1 (3) (1955) 289] and came up with the concept that in a turbulent field there is a maximum capacity of counter flow devices (trays or packings) that is a function of vapor velocity and system properties and is independent of the hardware parameters. He developed a model using data obtained from what was believed to be the highest capacity device known—high open area dualflow (DF) trays (29% hole area) at spacings of 24 to 96 in. A revised model was developed by Stupin [F.R.I. Topical Report 34, Special Collections Section, Oklahoma State University Library, 1965] in 1965 based on additional data, primarily at high pressure, and concepts developed by Levich [Physicochemical Hydrodynamics, Prentice-Hall, Englewood Cliffs, NJ, 1962]. At that time it was recognized that the relatively few experimental data points at low liquid loads tended to fall below model projections. This was not considered to be a problem since the vapor rates in question are normally only encountered in vacuum operations and in 1965 tray pressure drop was the governing factor in vacuum. Recent experimental work with modern, high capacity, low pressure drop devices confirm that at low liquid rates there appears to be a capacity ceiling which is independent of liquid loading. It should be noted that the liquid loading effect was empirical in all versions of the model. This was necessary since the theoretical development was based on the stability and/or deformation of a single drop.

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1. Introduction

1.1. What do we mean by capacity?

The capacity of vapor/liquid contacting devices can be presented in one of two ways: the combination of vapor and liquid rates at which it becomes hydraulically inoperable or the combination of vapor and liquid rates at which performance (usually mass transfer performance) becomes unacceptable. From the point of view of the user, the capacity of a tower is the maximum feed rate that it can handle consistent with satisfactory performance. Unfortunately, using a criterion of separation quality rather than hydraulic inoperability presents a number of problems. First, much device development and testing is done using simulators, air–water or air–test fluid (such as Isopar). This makes a hydrodynamic criterion for determining the maximum operable rate mandatory. In addition to total inoperability, a maxi-

mum pressure drop or quantity of captured entrainment are frequent choices [1,2]. Mass transfer studies can be done using NH₃/air/water to cross tie with the hydrodynamic results, but this always leaves questions regarding performance in a distillation system. Even when the testing is done in a distillation mode, capacity is frequently determined on a hydrodynamic basis since almost all efficiency measurements are made at a single value of L/V , total reflux, $L/V = 1.0$. This is done to eliminate a major source of experimental error since small errors in L/V can cause quite large errors in computed stage efficiency [3]. Attempts to correlate the rate at which efficiency is lost with the rate at which hydraulic inoperability occurs are complicated by the fact that the spread between them is a function of system properties and hydrodynamic flow regime. Fig. 1 compares the vapor rate of the last good efficiency measurement to the rate at hydraulic flood as a function of flow parameter for a single packing, Sulzer Mellapak 250.Y [4]. As may be seen, the two points coincide at high values of flow parameter (high pressure) and move consistently further apart as pressure (vapor density) is decreased.

* Corresponding author. Tel.: +1-405-385-0354; fax: +1-405-385-0357.
E-mail address: kunesh@fri.org (J.G. Kunesh).

Nomenclature	
C	Souders and Brown factor
C_D	drag coefficient
C_F	capacity factor at flood
D	drop diameter
D_{\max}	maximum stable drop size
F_D	drag force
F_g	gravitational force
g	gravitational acceleration
h	thickness of drop
dh	differential change in thickness
ΔP	pressure difference
S	surface area of drop
dS	differential change in surface
u_t	actual terminal velocity
u_{t0}	terminal velocity of a single solid sphere
v	vapor velocity
v_F	vapor velocity at flood
v_L	liquid velocity
V	volume of drop
w	mass flux
We	Weber number
We_c	critical Weber number
X	solids concentration
<i>Greek letters</i>	
μ_l	liquid viscosity
ρ_l	liquid density
ρ_v	vapor density
$\Delta\rho$	liquid density minus vapor density
σ	surface tension
$v_L\sqrt{\rho_l}/v\sqrt{\rho_v}$	flow parameter

As a result of the above, most capacity measurements and models use hydraulic inoperability to define maximum capacity or flood.

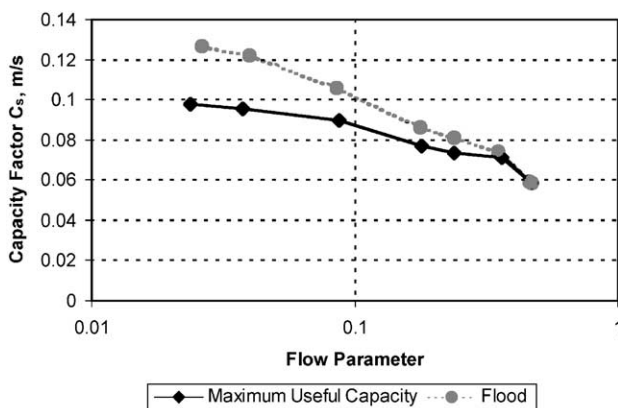


Fig. 1. Mellapak 250.Y.

2. Entrainment flooding

Massive entrainment or jet flooding is frequently the capacity limiting mechanism in counter current vapor liquid contacting devices. Because initial drop size and local vapor jet velocities are a function of the type of contacting device, hardware parameters will have a significant effect. The purpose of this work is to determine whether there is an upper limit or “ultimate capacity” which is independent of the hardware and a function of system properties only (“system limit”).

The earliest definitive work analyzing entrainment flooding was that of Souders and Brown [5]. They considered a spherical drop ejected over the mass of liquid on tray. The two forces acting on it are drag from the ascending vapor:

$$F_D = C_D \left(\frac{1}{2} \rho_v v^2 \right) \left(\frac{1}{4} \pi D^2 \right) \quad (1)$$

and gravity:

$$F_g = \frac{1}{6} (\pi D^3) g \Delta\rho \quad (2)$$

When the drag of the ascending vapor equals the force of gravity, the drop will remain suspended and at higher velocities it will be entrained upward with the vapor. Solving for the suspending (or terminal) velocity they obtained the following:

$$v = \left(\frac{4 D g \Delta\rho}{3 C_D \rho_v} \right)^{1/2} \quad (3)$$

Converting the above to mass velocity per unit area (mass flux), $w = v\rho_v$, and grouping drop size, drag coefficient and constants into a factor C which had to be empirically determined as a function of hardware parameters and other system properties, they came up with what is now referred to as the “permissible mass velocity” (PMV) method:

$$w = C [(\Delta\rho)\rho_v]^{1/2} \quad (4)$$

They published a table of C values calculated for commercial columns “. . . operating at approximately the maximum vapor load compatible with satisfactory products”. Parameters in the table were operating pressure, plate spacing and surface tension. They produced a plot of C as a function of plate spacing at varying surface tensions noting that the dominant factors in entrainment should be drop size, which is related to surface tension, and plate spacing since much entrainment is from the throwing of droplets by jets emerging from the bubble cap slots. These jets will dissipate with increasing plate spacing.

The grouping $v(\rho_v/\Delta\rho)^{1/2}$ from (3) has become known as the “capacity factor” and is widely used as a correlating parameter today. Note that the area basis for the vapor velocity must be specified.

2.1. Drop stability

Drop stability was analyzed by both Hinze [6,7] and Levich [8]. Although they followed slightly different lines

of development, they came to essentially the same functional relationship, differing only in the constants. Hinze considered the balance between the force tending to deform a drop $\rho_v v^2/2$ with the surface tension force holding drops together $4\sigma/D$ and postulated that there was a critical Weber number,

$$We_c = \frac{\rho_v v^2 D}{2\sigma} \quad (5)$$

beyond which the drop would shatter. Evaluating data available at the time, all of which had been obtained by observing drops falling in a stagnant vapor (air), he concluded that the critical Weber number was about 10^6 . Since internal drop circulation influences its stability, there can be a liquid viscosity effect. Again, based on data available at that time, he concluded that liquid viscosity only became a factor when $\mu_1^2/\rho_1\sigma D \gg 1$.

3. System limit or ultimate capacity

During the period 1959–1961 Tek [9,10] combined Hinze's drop stability work with the entrainment flood concept discussed above. He postulated that if there is a distribution of drop sizes in a rising vapor stream, small drops will be entrained, large drops will fall and drops of a critical size will be suspended. If the suspended drops are at the critical Weber number, larger drops will shatter and there will be no net downward flow of liquid. This is the concept of "system limit" or "ultimate capacity". He then developed an empirical correlation for critical drop size based on available data from a four foot diameter column containing 29% hole area dualflow (DF) trays at spacings from 2 to 8 ft using the systems cyclohexane/*n*-heptane at 0.27 and 1.65 bar and *i*-C₄/*n*-C₄ at 11.3 bar. The liquid rate term was a simple linear function of superficial liquid velocity. His model was as follows:

$$v_F = \left(\frac{\sigma}{\rho_v}\right)^{1/2} - 1.4 \left(\frac{\Delta\rho}{\rho_v}\right)^{1/2} v_L \quad (6)$$

or multiplying both sides by $(\rho_v/\Delta\rho)^{1/2}$ to convert to a capacity factor basis:

$$C_F = \left(\frac{\sigma}{\Delta\rho}\right)^{1/2} - 1.4 v_L \quad (6A)$$

The above is dimensionally inconsistent and is based on the use of US traditional units.

Using the properties of the cyclohexane/*n*-heptane system at 1.65 bar given in Table 1, this model yields a system limit capacity factor of 0.58 ft/s (0.177 m/s) when extrapolated to zero liquid rate.

Manning [11] extended the concept by designating the critical Weber number as We_c and the associated maximum stable diameter as D_{max} . Rearranging (5) to solve for D_{max}

Table 1
Cyclohexane/*n*-heptane system at 1.65 bar

	SI units	US traditional units
ρ_v	5.33 kg/m ³	0.33 lb/ft ³
ρ_l	629 kg/m ³	39 lb/ft ³
σ	0.013 N/m	13 dyn/cm
μ_v	8.0E-06 N s/m ²	0.008 cP
μ_l	2.11E-04 N s/m ²	0.211 cP

yields

$$D_{max} = \frac{2\sigma We_c}{\rho_v v^2} \quad (7)$$

Substituting for D in (3) and rearranging yields

$$v^4 = \frac{8}{3} \frac{g}{C_D} We_c \frac{\Delta\rho \sigma}{\rho_v^2} \quad (8)$$

Taking the fourth root and multiplying both sides by $(\rho_v/\Delta\rho)^{1/2}$ yields

$$C_F = v \left(\frac{\rho_v}{\Delta\rho}\right)^{1/2} = \left[\frac{8}{3} \frac{g}{C_D} We_c\right]^{1/4} \left[\frac{\sigma}{\Delta\rho}\right]^{1/4} \quad (9)$$

where C_F is defined as the capacity factor at flood. Manning presents results for several systems and devices noting that they average a maximum capacity about 38% of the maximum calculated from the above based on using a We_c of 7–10 based on Hinze's first work [6]. He also presents experimental results for devices using centrifugal force for vapor–liquid separation which indicate a much closer approach to the theoretical may be possible.

Again using properties of the cyclohexane/*n*-heptane system at 1.65 bar from Table 1, the Manning model predicts a system limit capacity factor of 0.257 m/s (0.842 ft/s) when using Hinze's original $We_c = 10$. In a later publication Hinze [7] analyzed liquid droplets being emulsified in a second liquid and found that We_c for this case was closer to 1.2. Applying this in Eq. (9) results in a system limit capacity factor of 0.16 m/s (0.524 ft/s) for the xylene system. A fairly modern proprietary tray supplier's design manual [14] predicts a maximum capacity factor of 0.17 m/s (0.56 ft/s) for all systems at 36 in. and higher tray spacings if the model is extrapolated to zero liquid rate. However, it places a ceiling of 90% of that value in the low liquid load region.

4. High pressure/high liquid rate model

At the time this work was underway in the early 1960s, most of the interest in ultimate capacity was at relatively high pressures and high liquid rates since pressure drop or entrainment flooding caused by vapor jets from the tray orifices ("jet flooding") usually set column size at pressures from vacuum to one or two atmospheres. Reviewing new data at pressures up to 34 bar, Stupin [12] reported that the

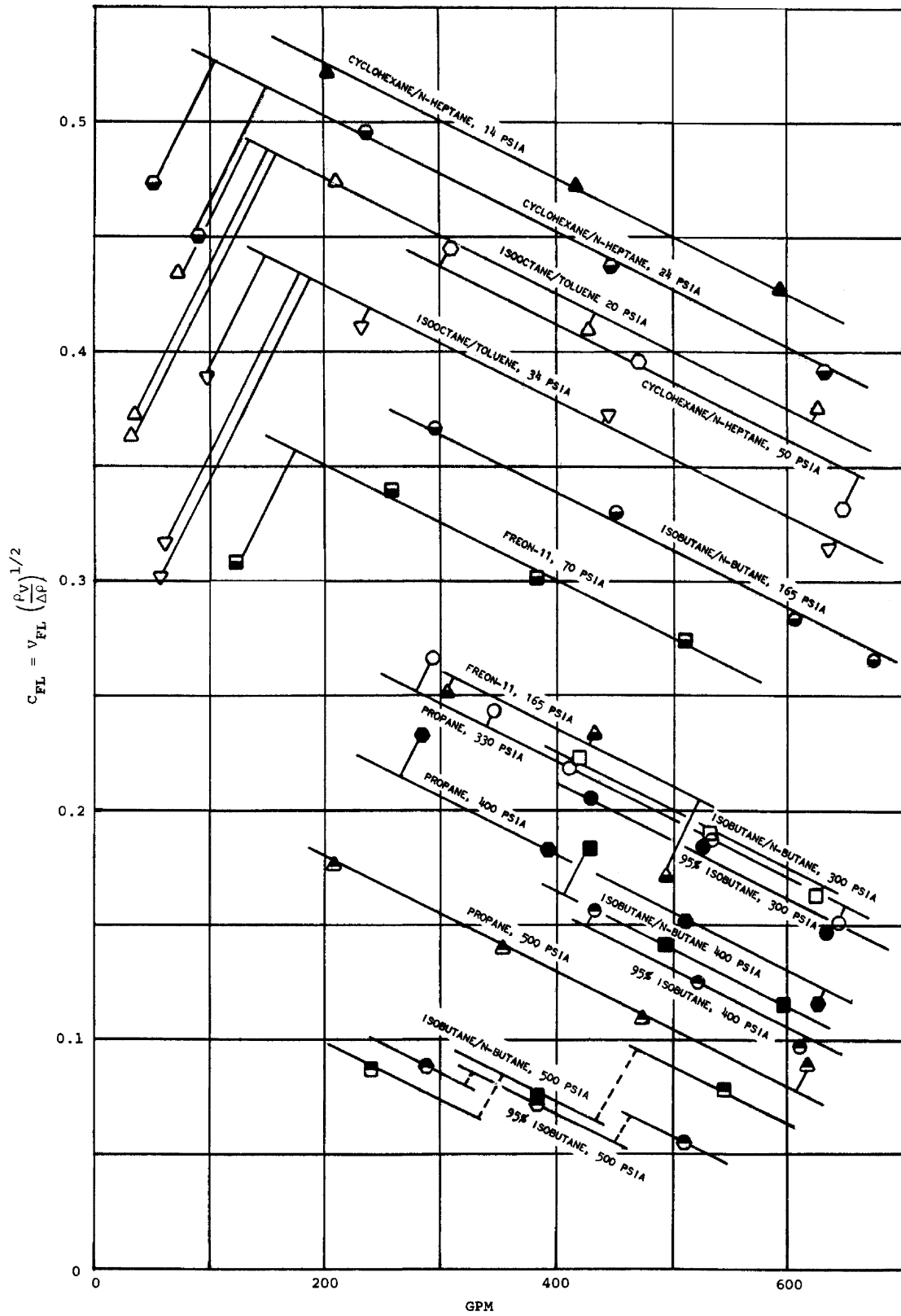


Fig. 2. Ultimate capacity of 29% open area dualflow trays.

previous Tek correlation was conservative (at least for high liquid rate, high pressure systems) and proposed following the model development presented by Levich [8] which had recently been translated from the Russian.

Levich considered an arbitrary drop having surface S , thickness h and volume V falling in a vapor. The velocity of fall creates a pressure differential around the drop,

$$\Delta P = \frac{1}{2} \rho_v v^2 \quad (10)$$

which is resisted by capillary forces. The drop is deformed and acquires a steady shape relative to the velocity v (if the velocity is such that the deformation exceeds the ability of the capillary force to resist, the drop shatters). The balance between pressure and capillary forces may be written in the form

$$\Delta P S dh + \sigma dS = 0 \quad (11)$$

or

$$\frac{dS}{dh} = -\frac{\Delta P S}{\sigma} \quad (12)$$

For an incompressible fluid,

$$V = Sh = \text{constant} \quad (13)$$

Differentiating and rearranging,

$$\frac{dS}{dh} = -\frac{V}{h^2} = -\frac{S}{h} \quad (14)$$

Equating (12) and (14) and solving for h yields

$$h = \frac{\sigma}{\Delta P} = \frac{2\sigma}{\rho_v v^2} \quad (15)$$

When the drop reaches terminal velocity, drag balances gravity with the result that

$$C_D \frac{\rho_v v^2}{2} S = \Delta \rho g V \quad (16)$$

Substituting (13) and (15) finally yields

$$v = \left(\frac{4g}{C_D} \right)^{1/4} \left(\frac{\Delta \rho \sigma}{\rho_v^2} \right)^{1/4} \quad (17)$$

The basic form matches Manning's results, differing only in the constant. Again using the cyclohexane/*n*-heptane system properties at 1.65 bar and using a drag coefficient, $C_D = 1.0$, as recommended by Levich, Eq. (17) converted to a capacity factor form predicts a system limit value of 0.17 m/s (0.555 ft/s), about 5% lower than the original Tek model. However, at the end of his derivation, Levich cautions that "... what is frequently encountered in practice is not the motion of individual drops, but the motion of a whole system or column of drops, moving at small distances from each other. In this case, the conditions of motion change... interaction between drops plays an important role and, to a large extent, determines the nature of motion of the system".

Extending the data base used by Tek with high pressure data primarily obtained with 29% open area DF trays at tray spacings of 1.2 m, Stupin's final model became

$$v = 0.73 \left(\frac{1.4(\Delta \rho / \rho_v)^{1/2}}{1 + 1.4(\Delta \rho / \rho_v)^{1/2}} \right) \left(\frac{\sigma \Delta \rho}{\rho_v^2} \right)^{1/4} - 1.4 \left(\frac{\Delta \rho}{\rho_v} \right)^{1/2} v_L \quad (18)$$

In the above the constant 0.73 applies when the US traditional units from Table 1 are employed. The constant is 2.502 in SI units.

Multiplying by $(\rho_v / \Delta \rho)^{1/2}$ to put the relationship on a capacity factor basis it becomes

$$C_F = 0.73 \left(\frac{1.4(\Delta \rho / \rho_v)^{1/2}}{1 + 1.4(\Delta \rho / \rho_v)^{1/2}} \right) \left(\frac{\sigma}{\Delta \rho} \right)^{1/4} - 1.4 v_L \quad (19)$$

Again employing properties of the cyclohexane/*n*-heptane system at 1.65 bar and extrapolating to zero liquid rate, a capacity factor at system limit of 0.521 ft/s (0.159 m/s) is predicted. The basic linear liquid rate effect employed by Tek was retained even though it was recognized that there might be a problem at low liquid rates. Fig. 2 presents the data on which the liquid rate term was based. Note that Eq. (19) was originally derived and published in traditional US units only. It may be seen that at rates below 40 m³/h m² (16 gpm/ft²) the data points all fall below the linear liquid rate effect line. The report notes that "the correlation may not be conservative" in the low liquid rate region but goes no further since other factors (usually pressure drop or jet flood) usually limited column throughput in this region.

5. Comparison of the models

Table 2 summarizes the predictions of the above models for the cyclohexane/*n*-heptane system at 1.65 bar and zero liquid rate. As may be seen, they are all close to one another with the exception of the original Manning which used a critical Weber number of 10 which was based on free falling drops in air. When the value of 1.2 obtained from the study of liquid drops being emulsified is used, the results fall in line with the other predictions.

Table 2
Comparison of model predictions at zero liquid rate cyclohexane/*n*-heptane system at 1.65 bar

Model	C_F (m/s)
Tek	0.177
Manning	0.257
Manning, $We_c = 1.2$	0.16
Levich	0.17
Levich–Stupin	0.159
Tray supplier	0.17

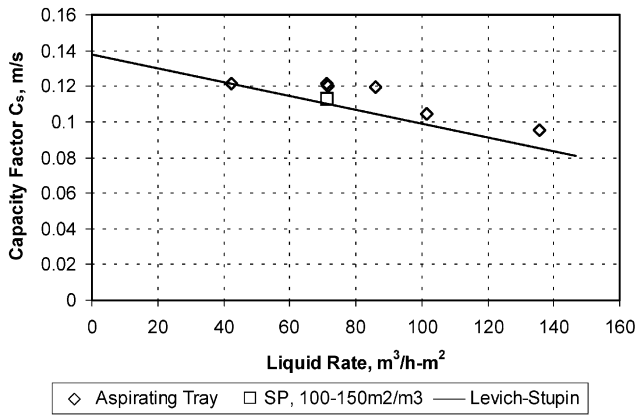


Fig. 3. Ultimate capacity: $i-C_4/n-C_4$; 6.89 bar.

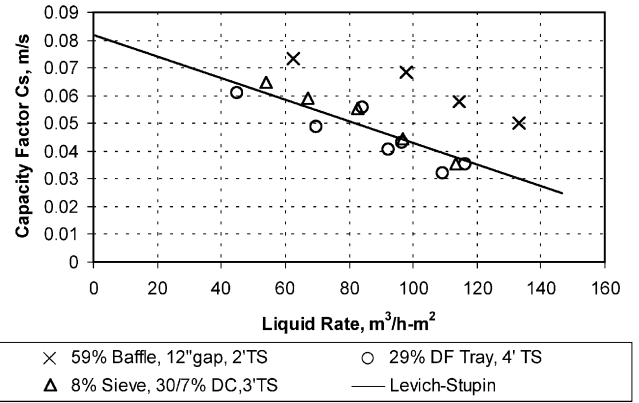


Fig. 6. Ultimate capacity: $i-C_4/n-C_4$; 27.6 bar.

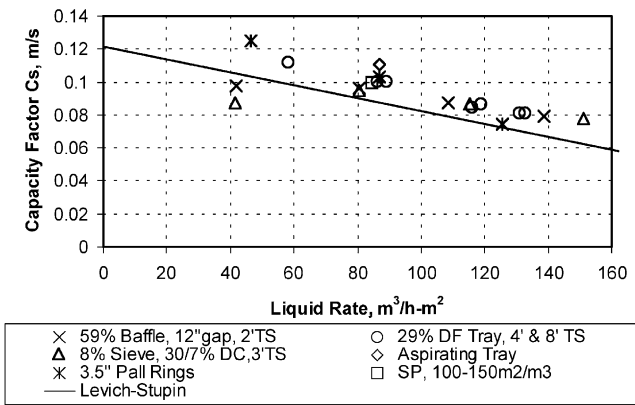


Fig. 4. Ultimate capacity: $i-C_4/n-C_4$; 11.4 bar.

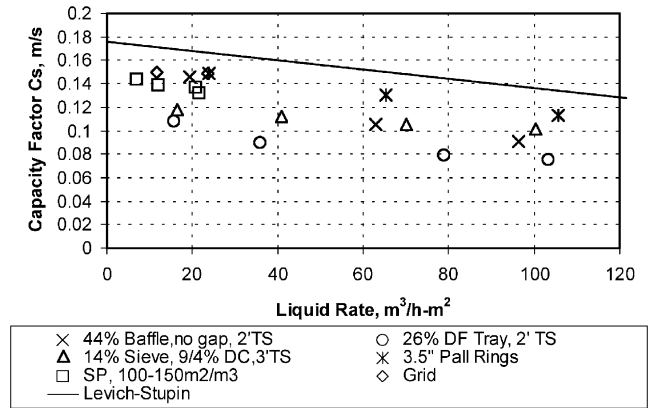


Fig. 7. Ultimate capacity: cyclohexane/n-heptane; 0.34 bar.

6. General applicability of model

Figs. 3–10 compare flooding capacities versus liquid rate for various trays, structured packing, and random packing to the predictions of the Levich–Stupin model. For each system

some of the highest capacity data measured by F.R.I. were chosen for comparison. DF and baffle tray column capacities have the greatest capacity for the larger tray spacings and open areas and downcomer flooding is not an issue. For several test systems a modern aspirating tray is shown in addition to the more conventional sieve tray. A modern high

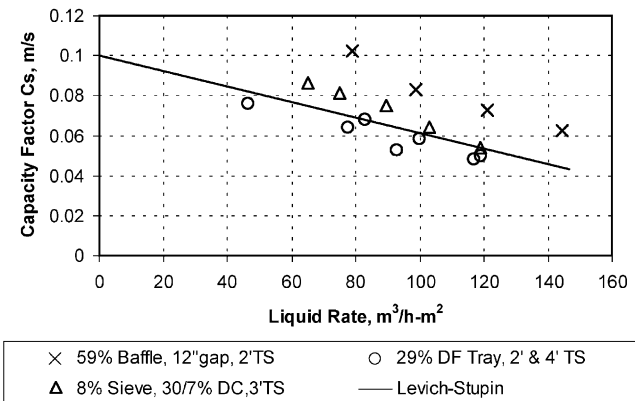


Fig. 5. Ultimate capacity: $i-C_4/n-C_4$; 20.7 bar.

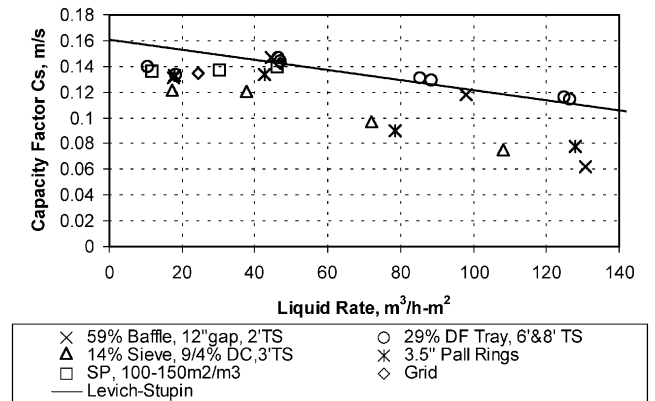


Fig. 8. Ultimate capacity: cyclohexane/n-heptane; 1.65 bar.

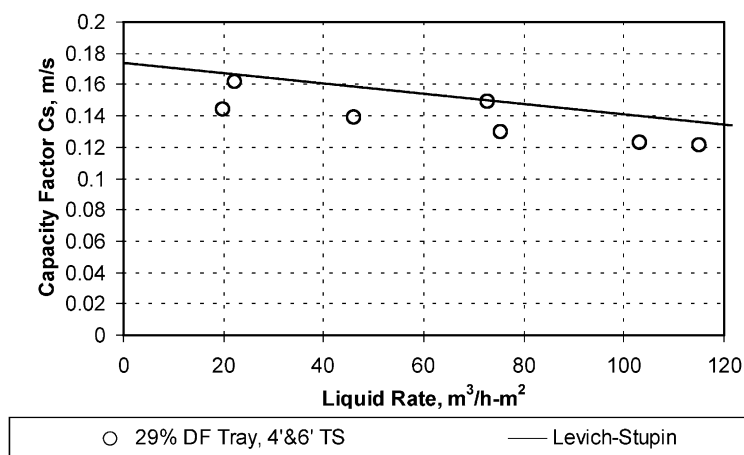
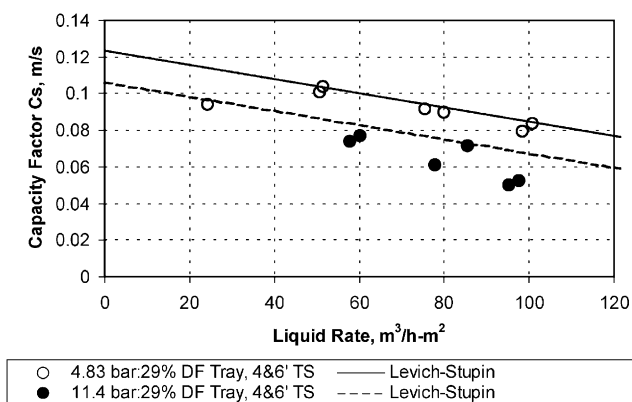
Fig. 9. Ultimate capacity: *o*-xylene/*p*-xylene; 240 mmHg.

Fig. 10. Ultimate capacity: Freon 11; 4.83–11.4 bar.

capacity structured packing (SP) is shown which has a low surface area (100–150 m²/m³). Also shown is a modern, high capacity grid (approximately 40 m²/m³). For random packings the larger the ring size the greater the capacity. Thus, 3.5 in. Pall rings (50 m²/m³) are shown for comparison. A variety of hydrocarbon systems and operating pressures are shown. The data represent a ratio of vapor to liquid density ranging from 0.001 to 0.2 and a surface tension ranging from 1 to 20 dyn/cm.

The 11.4 bar *i*-C₄/*n*-C₄ data best illustrates that the highest capacity trays and packings reach a similar upper limit on capacity. As shown in Fig. 4, structured packing, random packing, DF trays (Fig. 11), baffle trays (Fig. 12), sieve trays, and an aspirating tray with downcomers all show similar

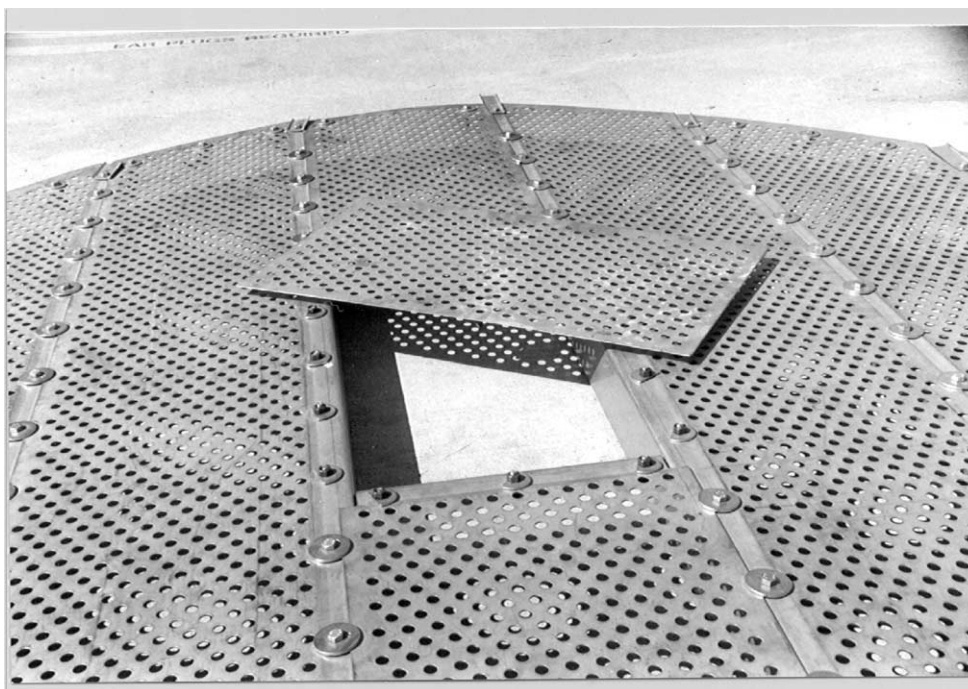


Fig. 11. A 16% open area dualflow tray.

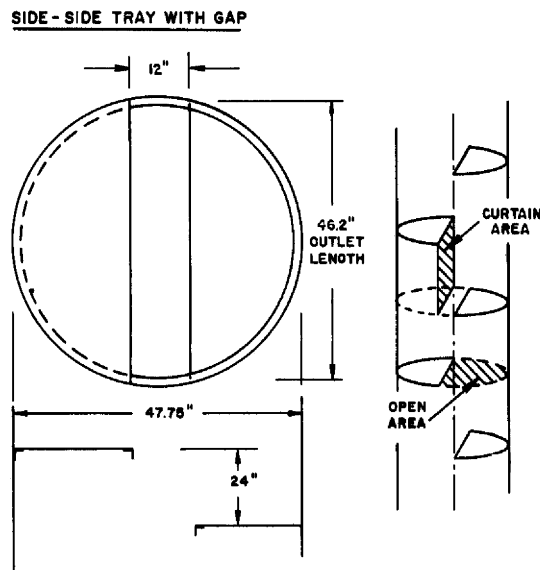


Fig. 12. Baffle tray.

flooding capacities. At the highest pressures (Figs. 5 and 6), the baffle tray which was gapped in the center allowing the liquid to flow down in a sheet as opposed to being dispersed has a greater capacity than the other devices, indicating that there is probably a difference in liquid rate effect depending on how the liquid is distributed.

The data clearly show that as the pressure increases, achievable capacity decreases. The highest capacity for the lowest pressure system shown, 240 mmHg xylene, has a maximum capacity of 0.16 m/s. The highest capacity measured for the highest pressure system, 27.6 bar *i*-C₄/*n*-C₄, is less than half this value at only 0.073 m/s. The Levich–Stupin model tends to underpredict ultimate capacity at the higher pressures, where liquid rates are the greatest. In the high pressure, high liquid rate region, the device that consistently shows a greater capacity than the model is a 59% open area baffle tray where there is a gap between baffles in the middle of the column. Thus, the vapor is contacting a falling sheet of liquid rather than a dispersed liquid phase.

In recent years, the introduction of high void fraction, low surface area grids and packings, both structured and random, have made operation at high gas velocities and low liquid rates, primarily at vacuum, feasible. Therefore, the issue of the system limit behavior at low liquid rates becomes important.

As previously mentioned, at the lowest liquid rates the capacity does not increase as the liquid rate is decreased. The greatest amount of experimental data below 20–40 m³/h m² which can be used to study this phenomenon is for the cyclohexane/*n*-heptane system at 0.34 and 1.65 bar (Figs. 7 and 8). These data clearly show that the capacity tends to flatten out or even decrease slightly as the liquid rate is reduced.

The Freon 11 tests (Fig. 10) were made to test the physical properties relationships. The density/surface tension ratio is about the same as for the butane system, but the density is twice as great. The model fits this system quite well.

7. Liquid rate effect

The theoretical derivation has no liquid rate effect because it is based on a single drop. As noted above, Levich warns that drop interaction will become important. In the settling of solids it is well known that settling velocity decreases as particle concentration increases [13]. Conversely, in the entrainment of droplets, the entraining gas velocity would be expected to decrease as droplet concentration increases. This trend matches the liquid rate effect determined from the experimental data. In the high liquid rate region, experimental data indicate that this effect is linear with liquid rate which may or may not be theoretically provable. In the low liquid rate region, the liquid rate effect would be expected to decrease and ultimately disappear as the drops become more dispersed. For the hindered settling of solids in the low liquid rate region, Perry and Green [13] suggest a relationship of the form

$$u_t = u_{t0}(1 - X)^n \quad (20)$$

where u_t is the actual terminal velocity, u_{t0} the terminal velocity of a single solid sphere, X the solid's concentration, and n varies from about 4.5 at $Re \leq 1$ to 2.5 at $Re \geq 10^3$.

As noted above, the Levich–Stupin model predicts a system limit capacity factor of 0.159 m/s (0.521 ft/s) for the cyclohexane/*n*-heptane system at zero liquid loading. The experimental data indicate a that maximum value of about 0.14 to 0.15 m/s (0.5 ft/s) holds for all devices at liquid loadings below 50 m³/h m² (20 gpm/ft²). If the relationship in (20) applies, this would indicate that ultimate capacity is reached with a free droplet concentration of 3–5 vol.% which is not unreasonable. Figs. 3–9 are for hydrocarbon systems which have a reasonably consistent density/surface tension/boiling point relationship. Freon 11 was chosen to stress the model since its density/surface tension ratio is about the same as butane but with twice as great a density. As may be seen in Fig. 10, the model held up quite well.

8. Conclusions

1. The concept that there is a system limit or ultimate capacity which is a function of system properties and independent of hardware parameters for counter current vapor/liquid contacting devices is valid.
2. As indicated by theory, there is a strong liquid rate effect which disappears as the liquid loading is decreased and the droplets become more dispersed.

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