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DISTILLATION TRAYS THAT OPERATE BEYOND THE LIMITS OF GRAVITY BY USING CENTRIFUGAL SEPARATION

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The interest of industry in super-high capacity fractionation trays has significantly increased in the last few years [1]. This paper focuses on a comparison of these technologies, using available data from open literature. In addition new research data for the ConSep tray will be presented using state of the art gamma-scanning capabilities. Four tray technologies fall in this category–The Shell Swirltube tray, Jaeger COFLO tray, Koch-Glitsch ULTRA-FRAC tray and the Shell ConSep tray. Publications on these trays have focused on a broad spectrum of applications–low liquid load operation such as glycol contactors [2] and low-pressure applications such as a hydrocracker main fractionator [3] to high-pressure systems such as refinery Superfractionators [4,5,7] and debutanizers [4,6].

LIMITATIONS OF 'CONVENTIONAL' HIGH CAPACITY TRAYS

The term "system limit" is often used as the point above which vapour and liquid velocities (depending on physical properties) become so high that excessive entrainment will always occur. As the pressure increases the density difference between the phases decreases and the velocities required to reach the so-called "system limit" get lower and lower. In this paper we have used the correlations given by Stupin and Kister [8] to calculate the system limit conditions. The system limit calculated in this way will be used in this paper to assess to what extent novel tray technologies can exceed the system limit. The technologies assessed in this paper are: Jaeger COFLO tray [9], Koch-Glitsch ULTRA-FRAC tray [2,10,11] and Shell ConSep tray [3–7]. These trays have all used some kind of separator device to prevent excessive entrainment as shown below in Table 1.

Clearly these trays differ in the type of contact and separation devices used. Therefore comparing and evaluating these different internals requires a closer look at the performance of the de-entrainment devices used in these trays.

Table 1. Various types of Super-high capacity trays and their differences

Tray type	Contact & separation zones	Contact type	De-entrainment internal
Jaeger COFLO tray	Separate	Normal distillation tray	Baffle-type entrainment collector
Shell Swirltube tray	Combined	Centrifugal contact	Swirl tube separator
Koch-Glitsch ULTRA-FRAC tray	Combined	Centrifugal contact	Centrifugal separator
Shell ConSep tray	Separate	Normal distillation tray	Swirl tube separator

GAS-LIQUID SEPARATORS

For use in distillation trays the separator should have the following characteristics:

- High vapour/liquid separation efficiency (>95% to prevent substantial tray efficiency loss).
- Good turn-down performance.
- Low cost.
- Low pressure drop.
- A good 'mass-transfer efficiency' will also be essential for those devices where contacting and separation are combined in a single element.

The baffle-type entrainment collector of the COFLO tray and the swirl tube separator in the Shell ConSep tray can be traced back to typical gas-liquid separators commonly used in industry i.e. the vane-pack mist-eliminators and the cyclonic separators. Although both of these devices have high de-entrainment efficiency, they differ in performance in terms of the maximum vapour and liquid loads that they can handle. While the vane-pack and cyclonic separators can handle high vapour loads at low flow parameters the performance changes markedly at high pressures and/or increased liquid loads. [12–14] There are two reasons for this. Firstly, vane packs generate the centrifugal forces ('g' forces) through the oscillatory gas flow path between the plates or baffles whereas the cyclonic separators use swirlers to impart strong axial and radial flows to the two-phase flow. Because of the use of swirlers, cyclonic separators generate higher 'g' forces as compared to the vane packs and hence have higher capacity. Secondly, at higher liquid loads re-entrainment of liquid from the vane surfaces becomes predominant and hence their vapour handling capacity decreases dramatically. Cyclonic separators on the other hand can handle higher liquid loads quite well. Based on these considerations it is expected that the COFLO tray will be capable of operating beyond the system limit provided the liquid loads are not too high. In order to assess this point a correlation for the system limit is used which has been published by

Stupin and Kister [8]:

$$C_1 = 0.445^*(1-F)(\sigma/\Delta\rho)^{0.25} - 1.4L \text{ which can be rewritten to:}$$

$$C_1 = \frac{0.445^*(1-F)(\sigma/\Delta\rho)^{0.25}}{1+1.4^*\phi^*\sqrt{\Delta\rho/\rho_L}} \text{using the flow-parameter} = \varphi = \frac{M_l}{M_g}\sqrt{\frac{\rho_g}{\rho_l}}$$

$$C_2 = 0.356^*(1-F)(\sigma/\Delta\rho)^{0.25} \text{and } F = \frac{1}{1+1.4\left(\Delta\rho/\rho_g\right)^{0.5}}$$

where $C_{S,\ ult}$ = the smallest between C_1 and C_2.

Results for the C6C7 system at different pressures are shown in Figure 1. This figure confirms that the COFLO tray can operate above the system limit provided the liquid loads are relatively low (in this case below or close to a liquid load of $36 m^3/m^2/hr$). The rapid decline in capacity as the pressure is raised is most likely due to limitations in the liquid handling capacity of the applied separator system.

For the ConSep tray the swirlers have a typical maximum liquid handling capacity in the order of:

$$Lmax_{swirler} \approx 1100\ m^3/m^2/hr \text{ (based on swirler cross sectional area).}$$

While the maximum vapour capacity of the swirlers is:

$$Cmax_{swirler} \approx 1\ m/s \text{ (C-factor based on swirler cross sectional area).}$$

Due to geometrical constraints (depending on area required for downcomers etc.) only about 20%–30% of the column cross sectional area will be occupied by swirlers and therefore the liquid handling capacity of the ConSep separators will be about

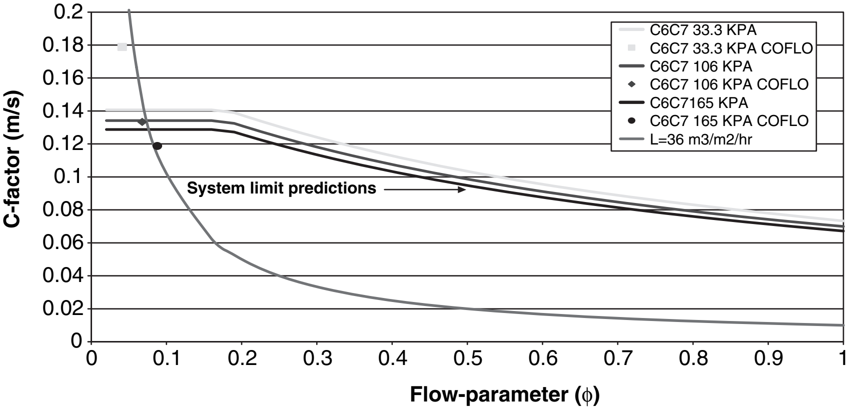

Figure 1. COFLO [9] flood points at different pressures compared with the system limit correlation. The red-line shows conditions at which the liquid load is $36 m^3/m^2/hr$.

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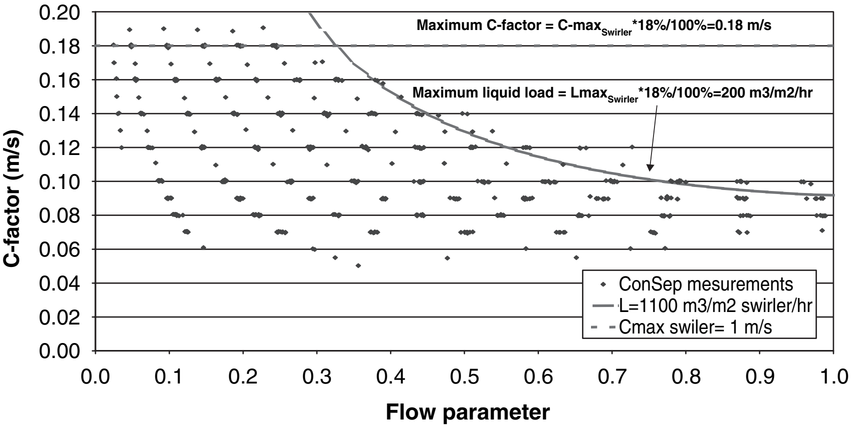

Figure 2. ConSep air-water data for a layout with 18% swirltube area.

$\mathrm{Lmax}_{\mathrm{column}} = \mathrm{Lmax}_{\mathrm{swirler}}{}^{*}\%$Swirler cross sectional area$/100\% \approx 200–320\ \mathrm{m}^3/\mathrm{m}^2/\mathrm{hr}$ based on total column cross sectional area. Judging from Figure 1 this is substantially higher than for the COFLO tray. Experimental results for the air-water system with a ConSep tray having 18% swirltube area are shown in Figure 2.

The distance between the sieve deck and the separator deck was varied between 200 and 600 mm. The results in Figure 2 are for a (vertical) sieve deck to separator deck distance of 400 mm (= height of froth contacting zone on sieve deck). A special feature of this ConSep test facility was that downcomer back-up limitations were prevented by using a very long downcomer. Under these conditions the maximum capacities achieved for the ConSep tray are clearly well described by the separator performance equations. Clearly both vapour and liquid loads are very high and illustrate the fact that the separators applied in ConSep will normally not pose any constraint. In fact the normal upper limit for a ConSep tray will be determined by downcomer back-up. Most of the liquid entering the downcomer has been 'degassed' in the separators and therefore a high froth density is typically achieved in the downcomer. This has been confirmed by visual observations for the air/water measurements. In addition detailed gamma-scans (Figure 3) show that the density at the bottom of the downcomers under hydrocarbon conditions also show a very high liquid content. The fact that the liquid (entering the downcomer) is very much degassed by the separator has also been reported for the COFLO [9] and ULTRA-FRAC tray [2]. Obviously this is an additional advantage for these kind of trays since the liquid handling capacity of the downcomer is improved when clear liquid is entering the downcomer instead of an 'aerated' liquid.

Figure 4 shows hydrocarbon data measured with ConSep in one of our research test facilities in Amsterdam (together with an FRI data-point which is in good agreement with

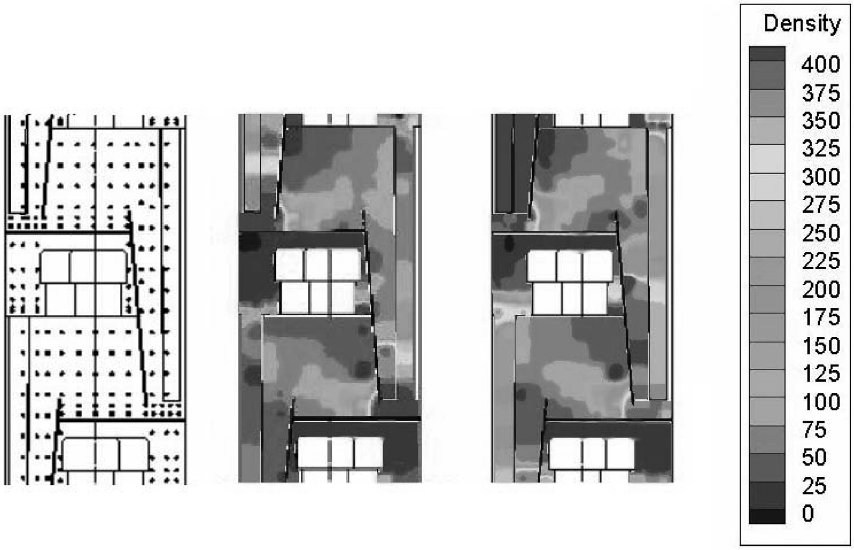

Figure 3. Gamma-scans for iC4/nC4 mixture at 11bar, tray spacing = 450 mm under total reflux conditions. Points in picture on the left show 'scan points'. The vapour load increases from left to right from Cf = 0.08 m/s to Cf = 0.11 m/s (Cf = based on total column cross sectional area).

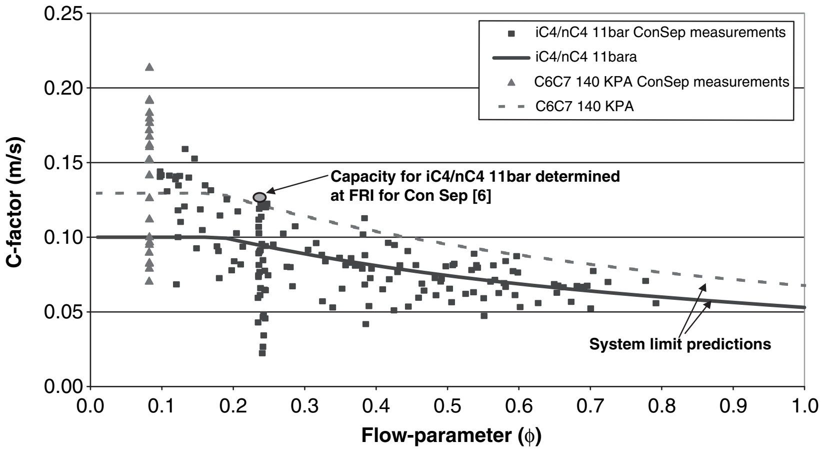

Figure 4. ConSep hydrocarbon data (iC4/nC4 11bar circulation and total reflux runs + C6C7 140 kPa total reflux runs).

our own results for iC4/nC4). The swirl-tube area for the C4 data was 18%. Important conclusions that can be drawn from Figure 4 are:

- Maximum operating points are well above the system limit for high as well as low flow parameters.
- The maximum operating points remain below the maximum (separator determined) values shown in Figure 2. This is due to the fact that the capacity for these layouts are constrained by downcomer backup.

Since the ULTRA-FRAC tray also contains an internal using centrifugal force for the vapor/liquid separation it is expected that this internal should also be able to operate beyond the system limit. Some air-water data for ULTRA-FRAC has been published as shown in Figure 5 confirming that the maximum operating conditions at low liquid flow rates indeed operate above the system limit for air-water.

Furthermore the data show that liquid handling capacity of these trays is indeed higher than for the COFLO tray as expected for a device where the separator is based on centrifugal forces. However, for the higher flow parameters the air-water data remain below the system limit. In addition it was reported in 2002 by Koch-Glitsch [10] that the ULTRA-FRAC tray does not exceed the system limit flood under high pressure conditions. The authors say, "These trays might be thought to be capable of exceeding system limit flood. However, this proves not to be the case." So what makes efficient gas-liquid separation at high liquid loads and high pressures so difficult? The answer probably lies in the 'g-forces' one is able to impart to the gas-liquid mixture

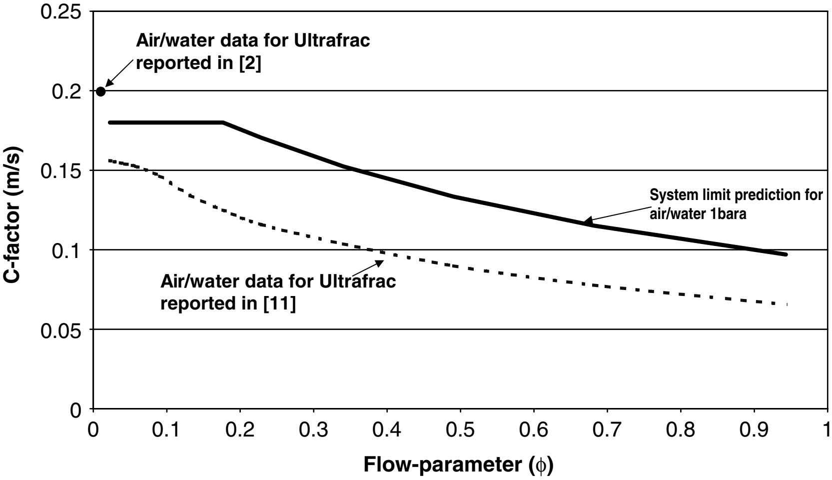

Figure 5. Maximum (air/water) capacity data for ULTRA-FRAC taken from references [2], [11].

once it leaves the tray. This translates into centrifugal acceleration-C.

$$C = \frac{V_r^2}{r} \quad [\mathrm{m/s^2}]$$

where,

V_r = radial velocity [m/s]
r = radius of travel [m]

Centrifugal separators provide the radial velocity via swirlers present at the inlet side. Exact swirler dimension have not been published for ULTRA-FRAC or ConSep. However, based on pictures in the open literature [6,15] it is obvious that the diameter of the ConSep swirlers are probably a factor 2–3 smaller than used for ULTRA-FRAC which contributes to high g-forces and improved separation of ConSep swirlers under high pressure conditions.

TRAY EFFICIENCY

For 'conventional' trays with long flow-path lengths tray efficiencies well above a 100% are often reported. Values above 100% are mostly the result of some degree of staging. For the super-high capacity trays discussed in this paper staging effects are likely to be more or less absent. Consequently it is expected that the maximum attainable efficiency for these devices will always be below 100%.

For the ConSep tray and the COFLO tray it is to be expected that the overall tray efficiency is determined by two contacting steps:

- Contacting on the tray deck (should be at least the point efficiency)
- Additional contacting in the separator section (e.g. high g-forces in ConSep)

Table 2. Prediction of tray efficiency with the O'Connell correlation for Super-high capacity trays and comparison with observed efficiency

		Efficiency	
Tray	Application	Actual (%)	O'Connell predicted (%)
ConSep Tray [6]	IC4/nC4 at 11 bar	89	82
COFLO tray [9]	C6/C7 at 0.33 bar	60	55
	C6/C7 at 1.06 bar	70	58
	C6/C7 at 1.66 bar	75	63
ULTRA-FRAC tray [11]	Deethanizer	85	82
	Depropanizer	78–82	79
	Debutanizer	75–85	69

For the ULTRA-FRAC tray and the Shell Swirl-tube tray contacting is primarily taking place in a single separator/contacting device.

It has been reported [10] that the O'Connell correlation [16] leads to reasonably good predictions for the ULTRA-FRAC trays. This simple correlation relates the tray efficiency to liquid viscosity and relative volatility and is based on the test data from 31 plant columns.

$$E_{OC} = 0.492(\mu_L \alpha)^{-0.245}$$

where,

Eoc = Predicted tray efficiency
μ_L = Liquid viscosity (centipoise)
α = Relative volatility

In order to compare the data we have taken the same approach by comparing the O'Connell correlation predicted efficiencies with the measured efficiencies for the different super-high capacity trays. The data (Table 2) confirm that the O'Connel correlation provides a reasonably (conservative) estimate for the efficiencies.

CONCLUSIONS

Several super-high capacity trays are now available on the market. For low pressure/low liquid loaded systems all of these products have shown evidence for achieving capacities exceeding the system limit. This is clearly a breakthrough in distillation technology. For higher liquid loaded (often high pressure) systems it appears that the use of a centrifugal type separator is required to achieve large capacity gains beyond the system limit. Of the different trays evaluated in this paper the COFLO is the only one not using a centrifugal type separator and therefore it is to be expected that this tray will not exceed the system limit at higher pressures and/or higher liquid loads. The data reported for COFLO [9] support this assumption as operating beyond the system limit has only been demonstrated under low pressure conditions for this device. When comparing ConSep to ULTRA-FRAC it appears that both have a higher liquid handling capacity than COFLO and are also more suitable for operating at high pressures. The use of smaller swirl elements in ConSep should contribute to higher g-forces as compared to ULTRA-FRAC. Possibly this makes ConSep trays more suitable for operating under very high pressure conditions when gas-liquid separation becomes more difficult.

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