

# **REACHING NEW PERFORMANCE LEVELS WITH SURFACE ENHANCED RASCHIG SUPER-PAK STRUCTURED PACKINGS**

By

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## Abstract

In order to penetrate the popular  $250 \text{ m}^2/\text{m}^3$  structured packing market, a technically superior and commercially viable alternative to Raschig Super-Pak-300 (RSP-300) was developed: the Raschig Super-Pak-250 (RSP-250 wSE). It has a surface area of  $250 \text{ m}^2/\text{m}^3$ . The rows of sinusoidal waves within vertical packing sheets are surface enhanced to encourage greater turbulent radial spread of thin liquid film flows on the front and back of the waves on each sheet within an element. RSP-250 wSE was tested at SRP, University of Texas at Austin under identical total reflux conditions to RSP-300 [1] on the cyclohexane/n-heptane system at four operating pressures to characterise performance.

The effect of surface enhancement on the mass transfer efficiency of RSP-250 wSE compared to Raschig Super-Pak 300 without surface enhancement (RSP-300 woSE) is significant with consistently lower HETP values. On comparing with the Montz B1-250 and B1-250M [2] as well as F.R.I. tested Sulzer Mellapak M250Y and MellapakPlus M252Y at 0.34 and 1.65 bar (5 and 24 psia) system pressures [3], the hydraulic-efficiency results for RSP-250 wSE are outstanding.

For all system pressures, the pressure drop of RSP-250 wSE are significantly lower by an order of magnitude than the  $250 \text{ m}^2/\text{m}^3$  surface area standard structured packings and significantly less than the high capacity types at high flow rates. Combined with excellent efficiencies, the pressure drop per theoretical stage is even more impressive.

Given the outstanding hydraulic and mass transfer efficiency performance, the credentials of RSP-250 wSE competing in the  $250 \text{ m}^2/\text{m}^3$  surface area structured packing market can now be firmly established.

## 1. Introduction

At the 2006 AIChE Spring National Meeting, Raschig Super-Pak structured packing was introduced [1] that is fundamentally different to the standard and high capacity corrugated sheet metal structured packings. The familiar corrugated sheet metal packing types typically have a crimp angle of  $45^\circ$  ( $60^\circ$  for lower pressure drop) and vendors use various techniques in an attempt to optimise wetting by using surface enhancements and/or holes on the metal sheets. A common feature, however, is that both standard and high capacity structured packings have discreet crimped channels that force vapour-liquid traffic along preferred flow paths. Additionally the vapour-liquid traffic is forced into sharp directional changes at the packing layer interface when packing elements are vertically stacked at alternating  $90^\circ$  orientations. The net result is that the enforced vapour-liquid flow patterns within the 'closed' structure of a packing element do not necessarily utilize all of the available surface area for mass transfer and impose restrictive forces that affect capacity and pressure drop.

Raschig GmbH adopted a different approach in developing Raschig Super-Pak. It is a more open structure such that vapour-liquid traffic can flow freely within a packing element and at the layer interface where sharp directional changes are minimised. The first packing investigated was Raschig Super-Pak 300 without surface enhancement and from here on labelled RSP-300woSE. The open structure resulted in excellent hydraulic and mass transfer efficiency characteristics as verified in total reflux distillation tests at the Separations Research Program (SRP), University of Texas at Austin [1].

## 2. Background

The impressive performance of RSP-300woSE raised questions whether hydraulic-efficiency comparisons with a packing of surface area  $300 \text{ m}^2/\text{m}^3$  can be made with  $250 \text{ m}^2/\text{m}^3$  surface area was fair. Faced with this challenge, and in order to penetrate the popular  $250 \text{ m}^2/\text{m}^3$  structured packing market, a technically superior and commercially viable alternative to Raschig Super-Pak-300 was developed: the Raschig Super-Pak-250 (RSP-250 wSE). It has a surface area of  $250 \text{ m}^2/\text{m}^3$  and

consists of a regular sequence of sinusoidal waves above and below the plain of the metal sheet at a 45° angle of orientation. Packing sheets are arranged vertically side-by-side with opposing inclinations of rows of waves to form a layer as shown in Figure 1. Packing sheets are surface enhanced to encourage greater turbulent radial spread of thin liquid film flows on the front and back of the waves via numerous contact points on each sheet within an element. It maximises available surface area for mass transfer: a feature that is questionable with ‘closed’ channels in corrugated sheet types. Combined with lower shear stress forces encountered by countercurrent vapour flow, the net result is very high capacities, low pressure drops and excellent mass transfer performance.

Hydraulic performance of the new surface enhanced Raschig Super-Pak-250, RSP-250 wSE was studied at the University of Texas at Austin Separations Research Program (SRP). Pressure drop measurements with increasing gas capacity factor at select constant liquid rates using Air-Water are shown in Figure 2. RSP-250 wSE shows equivalent performance with RSP-300woSE at low vapour rates but lower pressure drops and greater capacity of up to 18% as vapour rate is increased.

### 3. Test Unit and Experimental Procedures

To further characterize the surface enhanced RSP-250 wSE, SRP conducted total reflux distillation tests using the cyclohexane/n-heptane (C<sub>6</sub>/C<sub>7</sub>) test system at operating pressures of 0.165, 0.33, 1.65 and 4.14 bar. Performance of the RSP-250 wSE structured packing is compared against the Montz B1-250 and B1-250M conventional and high capacity structured packings tested under identical conditions as reported by Olujic et al [2]. As with the RSP-300 test, the RSP-250wSE hydraulic and mass transfer data at 1.65 bar pressure are compared against B1-250 and B1-250M packing measurements at 1.03 bar since no runs were made at 1.65 bar. In addition results are compared against F.R.I. tested Sulzer Mellapak M250.Y and MellapakPlus M252.Y structured packings on the C<sub>6</sub>/C<sub>7</sub> at 0.34 and 1.65 bar test systems as reported by Pilling and Spiegel [3].

Distillation tests were performed in the SRP 0.43 m ID column with a bed height of 3.05 m. The liquid distributor used was the SRP high capacity narrow trough drip tube distributor, with 145 pour points/m<sup>2</sup> and liquid flow rate range of 5 to 50 m<sup>3</sup>/m<sup>2</sup>/h. A complete description of the experimental set up, operating procedures and computation of results can be found elsewhere [1,5].

Hydraulic results, in the form of pressure drop per unit height ( $\Delta P/H$ ), pressure drop per theoretical stage ( $\Delta P/Stage$ ), and mass transfer results (HETP) are all plotted against vapour rate ( $F_S$ -Factor) based on bottom of the column conditions.

## 4. Results and Discussion

### 4.1 Liquid Rate and Operating Pressure Effect on Efficiency

At all four pressures the effect of surface enhancement on the mass transfer efficiency of RSP-250 wSE compared to Raschig Super-Pak 300 without surface enhancement RSP-300woSE [1] is significant with consistently lower HETP values up to 50 mm. Representative examples at 0.33 and 1.65 bar are shown in Figure 3. With each operating pressure, the HETP is fairly constant up to the loading regime followed by a sustained dip in HETP values, indicative of improved mass transfer efficiency, prior to a sharp break in the HETP curve as the packing enters incipient flood. The exception was at 4.14 bar because the reboiler capacity had reached its upper limit prior to flooding. Regardless of pressure, HETP values are generally between 0.283 and 0.358 m.

Because RSP-250wSE, RSP-300woSE, B1-250M and M252.Y are high capacity devices it is worth noting how close the capacities are to System Limit as opposed to hydraulic flood. In reality 250 m<sup>2</sup>/m<sup>3</sup> surface area high capacity structured packings fall short of this condition in their mode of operation.

For each operating pressure, 90% of System Limit is superimposed in Figure 3 and subsequent figures below. As higher the operating pressure, the further away the abrupt rise in HETP for RSP-250wSE is with respect to the 90% System Limit such that hydraulic film flood occurs. Figure 3 shows an example at 1.65 bar operating pressure. With decreasing pressure, the rise in the RSP-250wSE HETP curve at the highest flow rates actually reach a critical point where it crosses the 90% limit. It is illustrated in Figure 3 with 0.33 bar operating pressure. Overall, it implies that as lower the operating pressure, the higher the tendency of high performance structured packings such as Raschig Super-Pak 250wSE to approach and even exceed 90% System Limit before it enters full hydraulic film flood.

## 4.2 Efficiency

Capacity-efficiency comparative plots of RSP-250wSE with the standard B1-250 [2] and F.R.I. tested M250.Y [3, 4] as well as the high capacity B1-250M [2] and F.R.I. tested M252Y [3] are presented in Figures 4 and 5 on the  $C_6/C_7$  1.65 bar test system. The RSP-250wSE HETP values are consistently lower than both the standard and high capacity  $250\text{m}^2/\text{m}^3$  surface area packings over the entire operating range. In Figure 4 the HETP in the mid capacity range at 1.65 bar pressure for RSP-250wSE is 0.334 m compared to 0.355 m and 0.385 m for B1-250 and M250.Y respectively. On comparing with the high capacity structured packings, the 0.334 m HETP value for RSP-250wSE in the mid capacity range is lower than 0.375 m for RSP-300woSE [1], 0.379 m for the B1-250M and 0.355 m for M252Y as shown in Figure 5.

At 0.33 bar operating pressure, the RSP-250wSE HETP values are consistently lower than both the standard and high capacity  $250\text{m}^2/\text{m}^3$  surface area packings as shown in Figures 6 and 7. Compared to the standard types, HETP in the mid capacity range for RSP-250wSE in Figure 6 is 0.342 m compared to 0.356 m with B1-250 [2] and 0.483 m for M250.Y [3,4]. On comparing with high capacity structured packings in Figure 7, the 0.342 m HETP for RSP-250wSE in the mid capacity range is lower than 0.387 m for RSP-300woSE [1], 0.413 m for B1-250M [2] and 0.374 m for M252Y [3].

## 4.3 Useful Capacity

For both test pressures, RSP-250wSE shows a clear maximum useful capacity advantage (defined above) compared to both the standard and high capacity structured packings. This is summarised in the Maximum Useful Capacity – Flow Parameter charts in Figures 8 and 9. Flow Parameter is  $(\rho_V/\rho_L)^{0.5}$  since  $L/V = 1$ . Each Figure shows the maximum useful capacity gain of RSP-250wSE over the standard and high capacity  $250\text{m}^2/\text{m}^3$  surface area packings [2,3,4] at 0.165, 0.33 and 1.65 bar operating pressures. Also shown is the 90 % System Limit for each pressure. Comparisons were not made at 4.14 bar because the reboiler capacity had reached its upper limit prior to flooding. Standard B1-250 is used as a reference point for useful capacity comparisons.

In Figure 8 the maximum useful capacity for RSP-250wSE is  $2.84\text{ Pa}^{0.5}$  compared to 2.32 and  $2.24\text{ Pa}^{0.5}$  for B1-250 and M250.Y at 1.65 bar. It represents a capacity advantage of 23 and 26 % respectively. Similarly at 0.33 bar, a value of  $3.42\text{ Pa}^{0.5}$  for RSP-250wSE is 27 % greater than for B1-250 at  $2.67\text{ Pa}^{0.5}$  and 34 % higher than M250.Y at  $2.56\text{ Pa}^{0.5}$ . At the lowest pressure of 0.165 bar the RSP-250wSE maximum useful capacity is  $3.72\text{ Pa}^{0.5}$  compared to  $2.88\text{ Pa}^{0.5}$  for B1-250, which represents an advantage of 29%.

Figure 9 shows the maximum useful capacity comparisons of RSP-250wSE against the high capacity structured packings. At 1.65 bar the maximum useful capacity for RSP-250wSE is  $2.84\text{ Pa}^{0.5}$  compared to 2.83, 2.61 and  $2.65\text{ Pa}^{0.5}$  for RSP-300 woSE [1], B1-250M [2] and M252.Y [3]. Useful capacities of RSP-250wSE and RSP-300woSE are almost identical, while there is a 7 to 9% increase over the B1-250M and M252.Y. At 0.33 bar, the RSP-250wSE maximum useful capacity of  $3.42\text{ Pa}^{0.5}$  is 1 % higher than RSP-300woSE at  $3.40\text{ Pa}^{0.5}$ , 8 % greater than B1-250M at  $3.17\text{ Pa}^{0.5}$  and 6 % higher than M252.Y at  $3.245\text{ Pa}^{0.5}$ . Maximum useful capacities of RSP-250wSE and RSP-300woSE are close to the 90% System Limit.

For the lowest operating pressure of 0.165 bar, a useful capacity of  $3.73 \text{ Pa}^{0.5}$  for RSP-250wSE exceeds the 90% System limit by 2% and is 4% greater than both RSP-300woSE and B1-250M with each having a maximum useful capacity of  $3.59 \text{ Pa}^{0.5}$ .

The useful capacity advantage of RSP-250wSE over the high capacity B1-250M and M252.Y structured packings is remarkable given that the flow channels in adjacent RSP-250wSE packing layers are at  $90^\circ$  with respect to one another when vertically stacked. Unlike the ‘closed’ channels of corrugated structured packings, the open structure of Raschig Super-Pak alleviates any restrictions in vapour-liquid flows at the element interface where layers touch.

#### **4.4 Hydraulic-Pressure Drop Comparison**

Pressure drop comparative plots of RSP-250wSE with both standard B1-250 [2], M250.Y [3, 4] and high capacity RSP-300woSE [1], B1-250M [2] and M252.Y [3] packings are presented in Figures 10 and 11 for 1.65 and 0.33 bar test pressures. No pressure drop data were reported at 1.65 bar for the F.R.I. M250.Y test in 1987. For both pressures RSP-250wSE pressure drops were less than the standard B1-250 and M250.Y by an order of magnitude and an average 37 % below that of the high capacity B1-250M and M252.Y at high flow rates. The pressure drop of RSP-250wSE tracks that of RSP-300woSE but is lower at the highest flow rates, particularly at 0.33 bar (see Figure 11).

The convergence of maximum useful capacity of RSP-250wSE, RSP-300woSE and M252Y at 0.33 bar operating pressure, suggests that the on-set of hydraulic film flooding is very close to or crossing the 90% System Limit. The pressure drop curve of Sulzers’ high capacity structured packing M252Y runs much more in line with both RSP-250wSE and RSP-300woSE than the Montz high capacity B1-250M. This may be an effect of the test facility as M252Y was tested at F.R.I. while B1-250M as well as both Raschig Super-Pak structured packings had been tested at SRP.

#### **4.5 Pressure Drop per Theoretical Stage Comparison**

Pressure drop per theoretical stage is an important parameter in evaluating different structured packing designs. Figures 12 and 13 show pressure drop per theoretical stage comparisons of RSP-250wSE both with standard B1-250 [2], M250.Y [3, 4] and high capacity RSP-300woSE [1], B1-250M [2] and M252.Y [3] packings. At 1.65 bar operating pressure, the pressure drops per theoretical stage of RSP-250wSE is consistently lower than both the standard and high capacity  $250\text{m}^2/\text{m}^3$  surface area packings. The pressure drops per theoretical stage of RSP-250wSE trends that of RSP-300woSE over the entire operating range. With 0.33 bar operating pressure, results are even more impressive such that the pressure drops per theoretical stage of RSP-250wSE is not only lower than the standard  $250\text{m}^2/\text{m}^3$  surface area packings but the high capacity B1-50M, M252.Y and RSP-300woSE as well.

On the whole the excellent hydraulic advantages of RSP-250wSE over the B1-250M and M252.Y high capacity structured packings is a remarkable result. Although adjacent Raschig Super-Pak 250 layers are rotated  $90^\circ$  with respect to one another when vertically stacked, the influence is insignificant because of the fully open structure that permits vapour-liquid traffic to flow more freely within a packing element and at the layer interface. This is in contrast to the B1-250M and M252.Y high capacity types with curvature of the corrugations gradually changing from  $45^\circ$  to  $0^\circ$  on vertical axis at one or both ends of the packing elements.

## 5. Conclusions

The effect of surface enhancement on the mass transfer efficiency of RSP-250 wSE compared to Raschig Super-Pak 300 without surface enhancement (RSP-300 woSE) is significant with consistently lower HETP values by at least 50 mm on all four test pressures. On comparing with the Montz B1-250 and B1-250M [2] as well as F.R.I. tested Sulzer Mellapak M250Y and MellapakPlus M252Y at 0.34 and 1.65 bar (5 and 24 psia) system pressures [3, 4], the hydraulic-efficiency RSP-250 wSE results are outstanding. The RSP-250 wSE maximum useful capacities are 29 and 23 % higher than B1-250 on 0.33 and 1.65 bar system pressures. For the same conditions, RSP-250 wSE measured efficiencies are around 20% better than B1-250. Comparisons against M250Y, indicate the capacity-efficiency advantages are even greater. When checked against the high capacity B1-250M and M252Y, the RSP-250 wSE maximum useful capacities are up to 6 to 8 % higher with up to 36 % lower HETP values (better efficiency).

For all system pressures, the pressure drop of RSP-250 wSE are consistently lower by an order of magnitude than the 250 m<sup>2</sup>/m<sup>3</sup> surface area standard structured packings and at least 35 % lower than the high capacity types at high flow rates. It also matches the pressure drop of RSP-300 woSE but the RSP-250 wSE pressure drop is lower at the highest rates in the loading regime. Combined with excellent efficiencies, the pressure drop per theoretical stage is even more impressive.

Given the outstanding hydraulic and mass transfer efficiency performance, the credentials of RSP-250 wSE competing in the 250 m<sup>2</sup>/m<sup>3</sup> surface area structured packing market are now firmly established.

## Acknowledgements

The authors would like to acknowledge the efforts of Professor Jim Fair, Dr. Frank Seibert, Mr. Christopher Lewis and Mr. Steve Briggs for their excellent work on the Raschig Super-Pak 250 with surface enhancement testing program.

## 6. References

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## Nomenclature

$C_6$		Cyclohexane
$C_7$		n-Heptane
$F_S$	$\sqrt{\text{Pa}}$ or $\text{m/s}(\text{kg/m}^3)^{1/2}$	Gas or vapour capacity factor = $u_s \cdot \sqrt{\rho_v}$
$H$	m	Packing height
HETP	m	height equivalent to a theoretical stage
$L$	kg/h	Liquid mass flow rate
$p$	bar	operating / system pressure
$u_L$	$\text{m}^3/\text{m}^2\text{h}$	superficial liquid velocity
$u_s$	m/s	superficial vapour velocity
$V$	kg/h	Gas or vapour mass flow rate

### Greek letters

$\Delta P$	Pa, mbar	Pressure drop
$\rho_L$	$\text{kg/m}^3$	Liquid density
$\rho_v$	$\text{kg/m}^3$	Gas or vapour density

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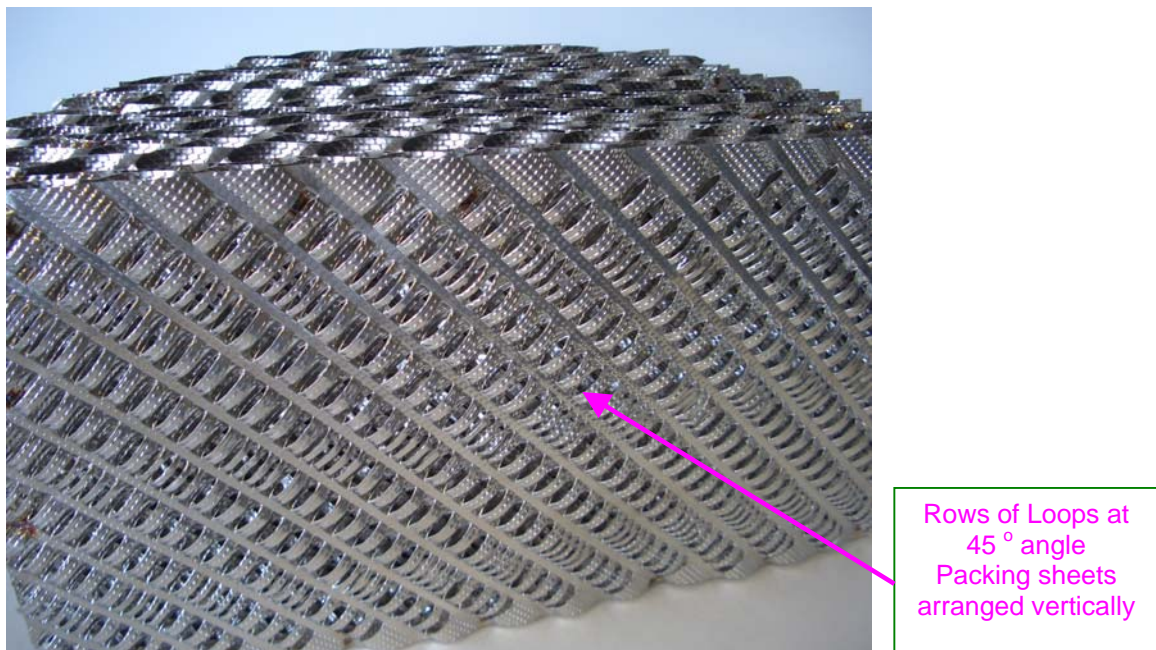


Figure 1. Photographs of Segment of Raschig GmbH Raschig Super-Pak 250 with Surface Enhancement, RSP-250 wSE

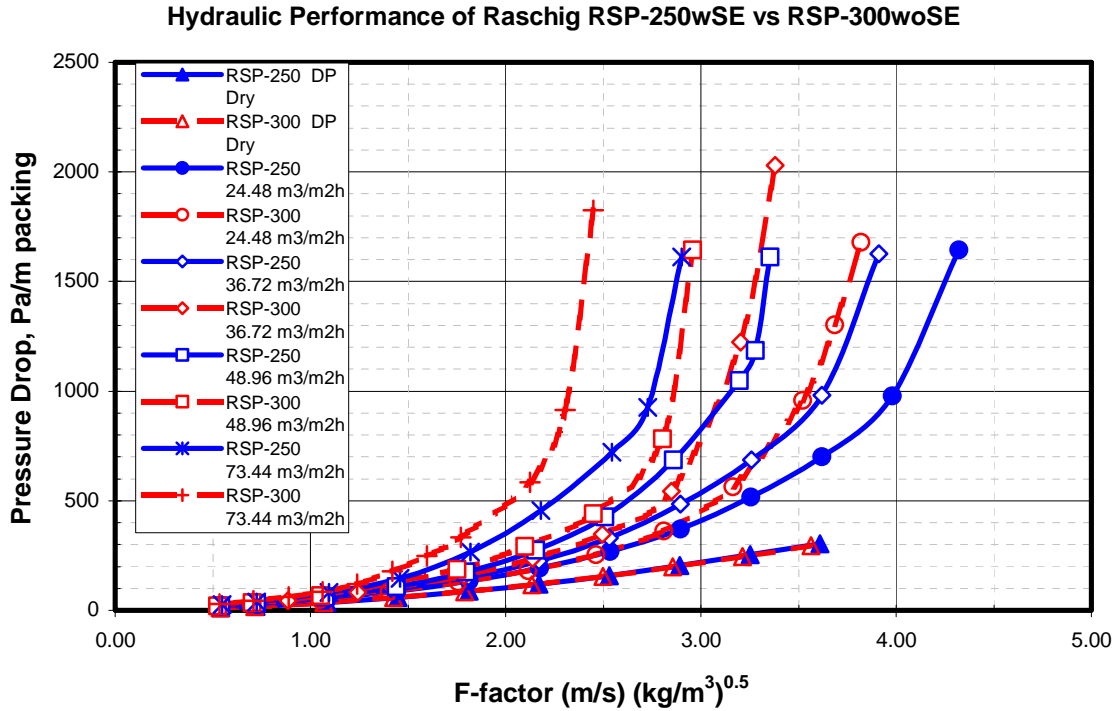


Figure 2. Pressure drop per meter packed height comparison of Raschig Super-Pak RSP-250wSE vs. RSP-300woSE for select constant liquid rates. Column ID 0.43 m, Bed Height 3.05 m. Air/water tests at Separations Research Program, University of Texas at Austin, Austin, Texas.

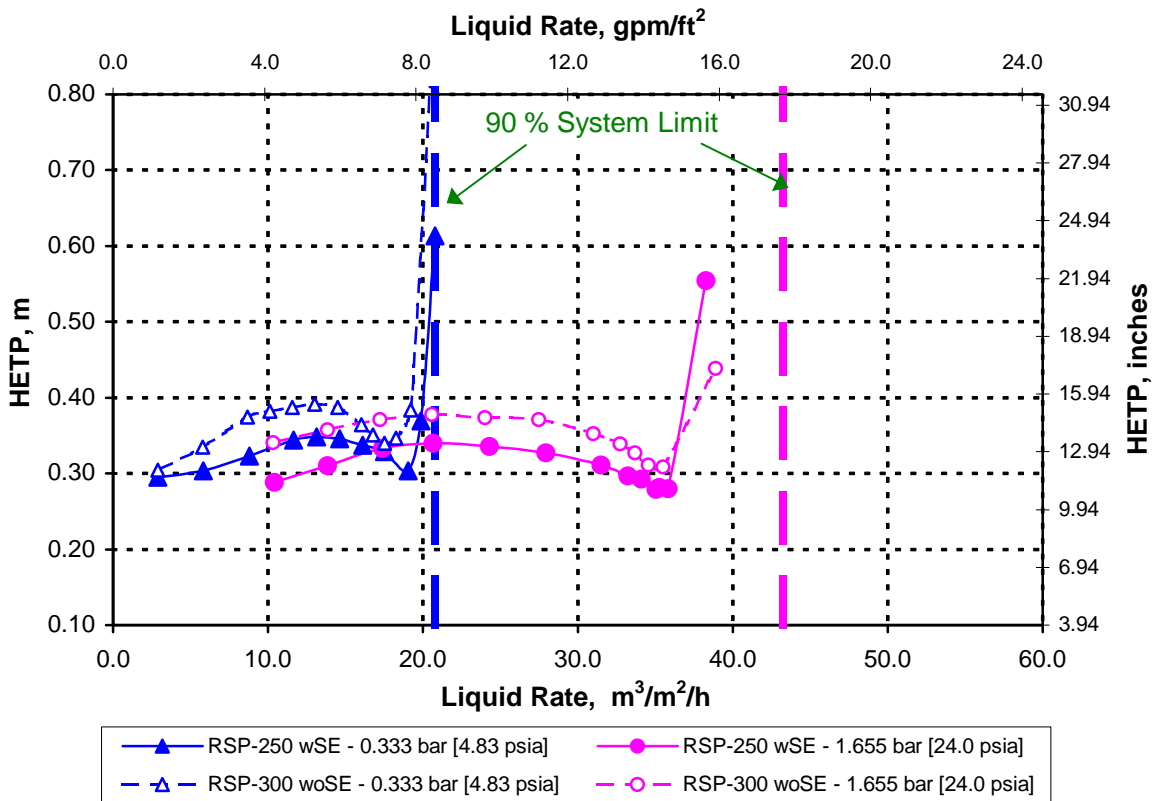


Figure 3. Effect of liquid rate and operating pressure on HETP of Raschig Super-Pak RSP-250wSE compared with RSP-300woSE at total reflux, 0.43 m I.D. SRP Column, 3.05 m Bed, C6/C7 System, High capacity drip tube distributor



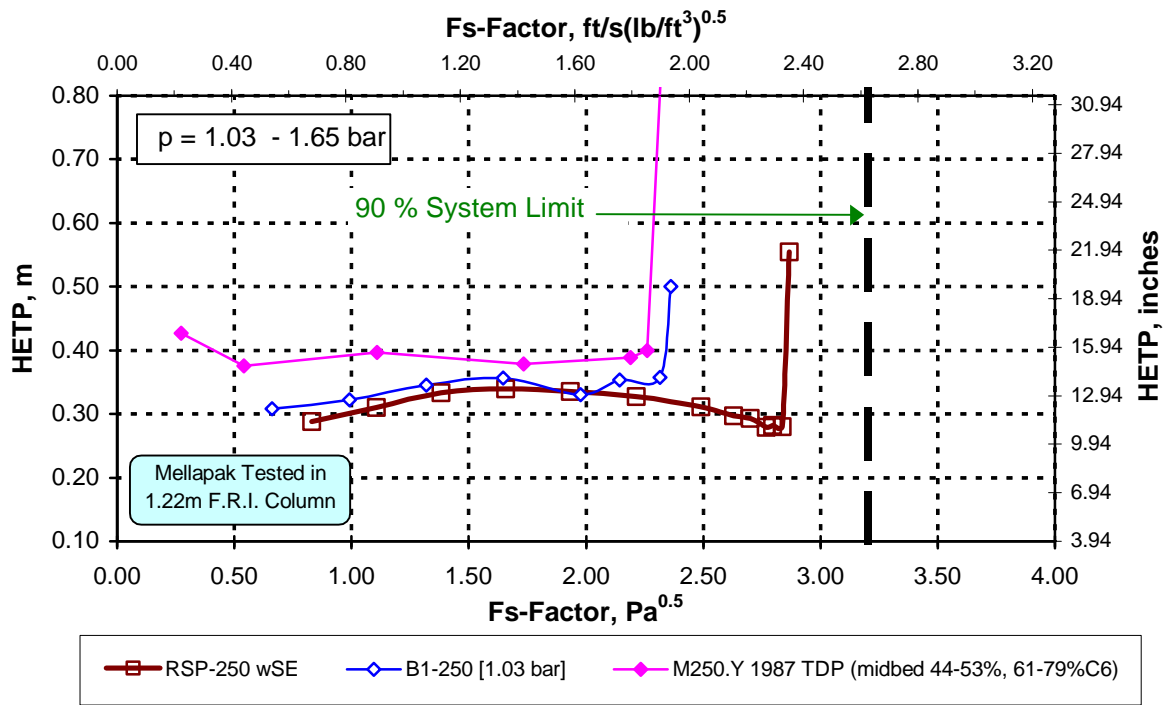


Figure 4 Mass transfer efficiency (HETP) comparison at total reflux. Raschig Super-Pak RSP-250 wSE vs. Standard B1-250 [1.03 bar] and M250Y (FRI 1987) at 1.655 bar, 0.43 m I.D. SRP column, 3.05 m bed, C<sub>6</sub>/C<sub>7</sub> system, High capacity distributors.

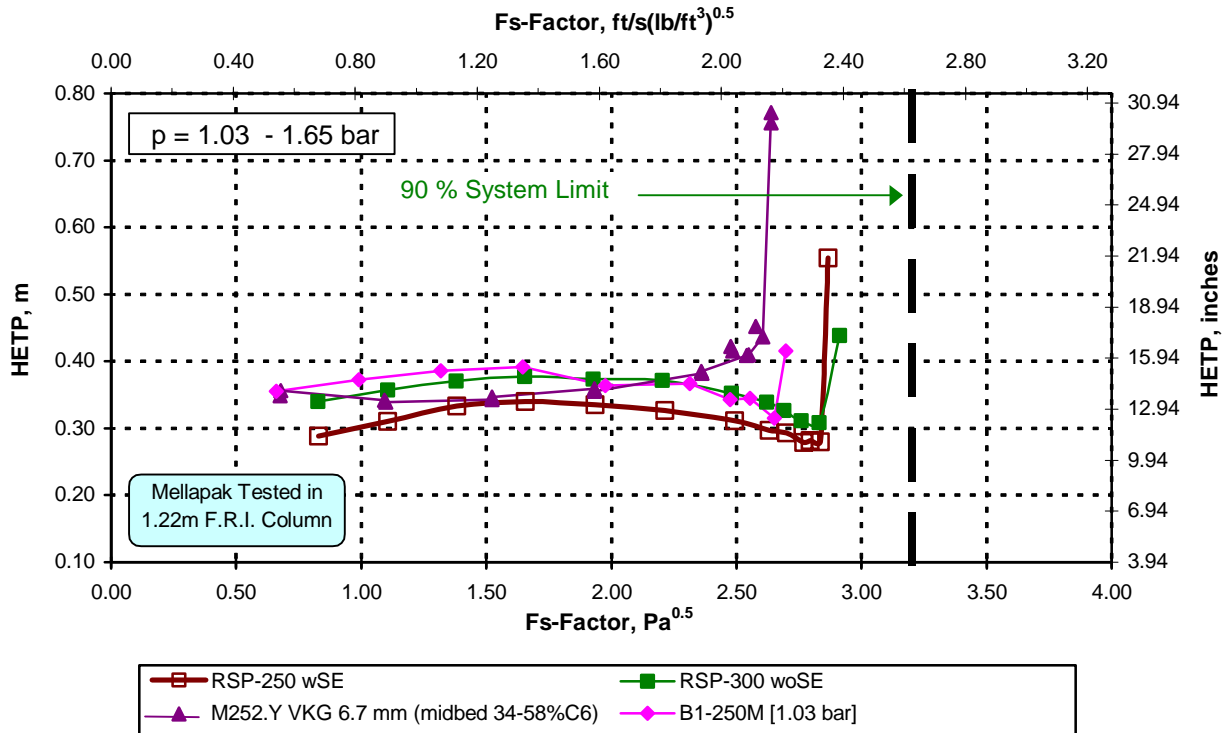


Figure 5 Mass transfer efficiency (HETP) comparison at total reflux. Raschig Super-Pak RSP-250 wSE vs. RSP-300 woSE, High Capacity B1-250M [1.03 bar] and M252Y (FRI) at 1.655 bar, 0.43 m I.D. SRP column, 3.05 m bed, C<sub>6</sub>/C<sub>7</sub> system, High capacity distributors

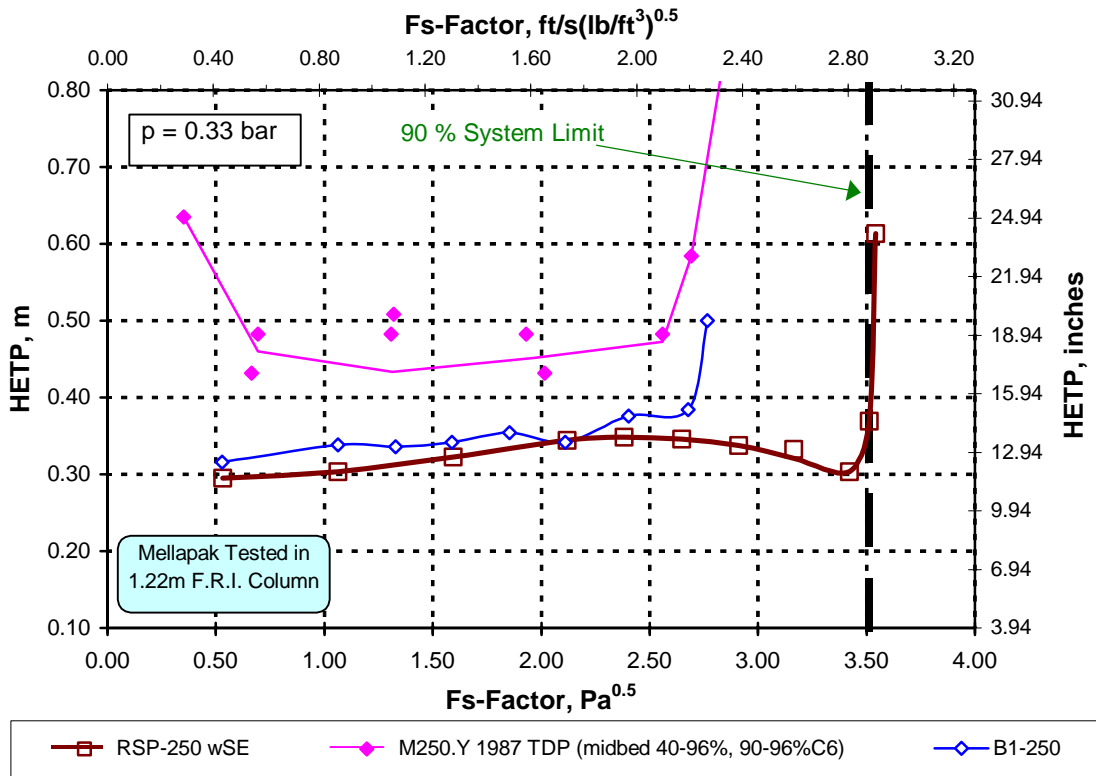


Figure 6 Mass transfer efficiency (HETP) comparison at total reflux. Raschig Super-Pak RSP-250 wSE vs. Standard B1-250 and M250Y (FRI 1987) at 0.333 bar, 0.43 m I.D. SRP column, 3.05 m bed,  $C_6/C_7$  system, High capacity distributors

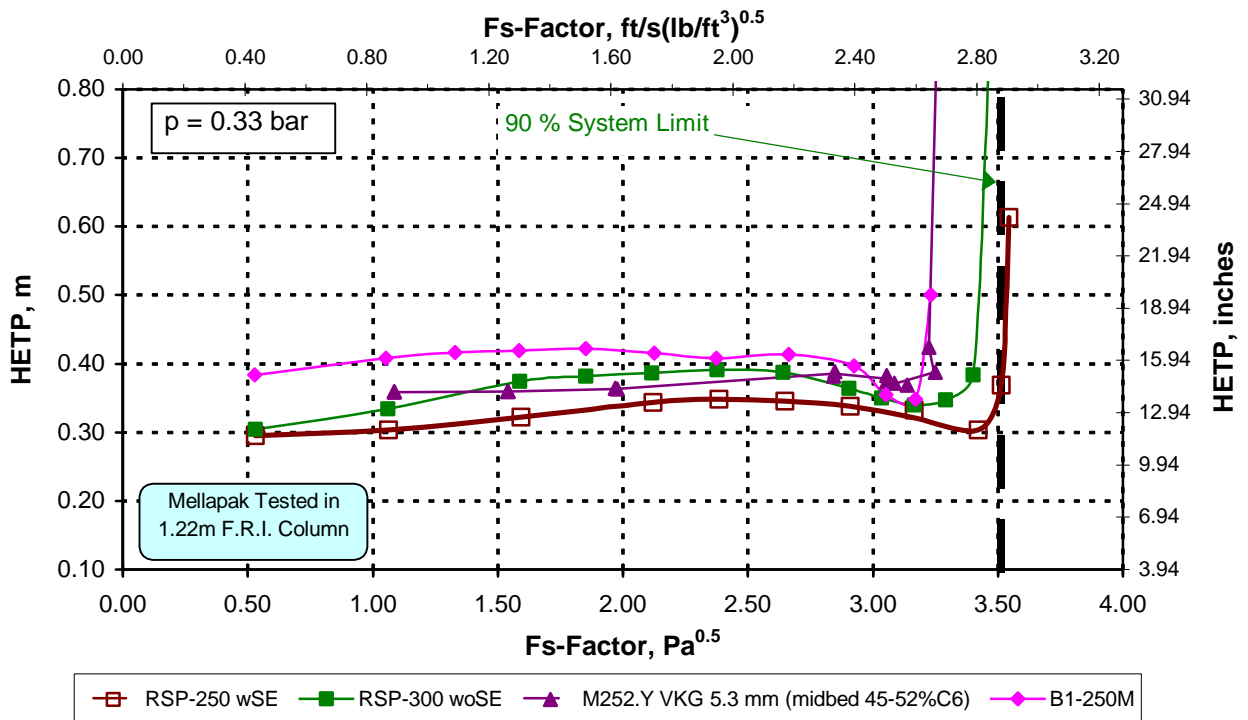


Figure 7. Mass transfer efficiency (HETP) comparison at total reflux. Raschig Super-Pak RSP-250 wSE vs. RSP-300 woSE, High Capacity B1-250M and M252Y (FRI) at 0.333 bar, 0.43 m I.D. SRP column, 3.05 m bed,  $C_6/C_7$  system, High capacity distributors.

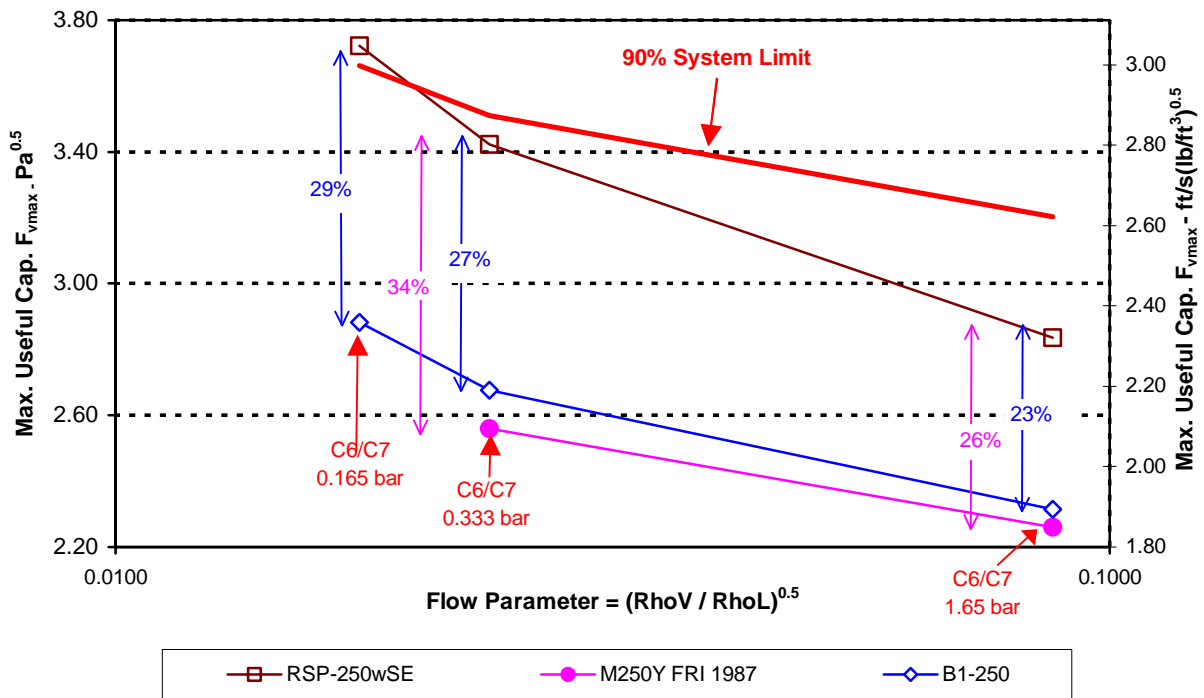


Figure 8. Maximum Useful Capacity based HETP at Different Pressures versus Flow Parameter Comparison. Raschig Super-Pak RSP-250 wSE vs. RSP-300 woSE, And Standard B1-250 and M250Y (FRI 1987)

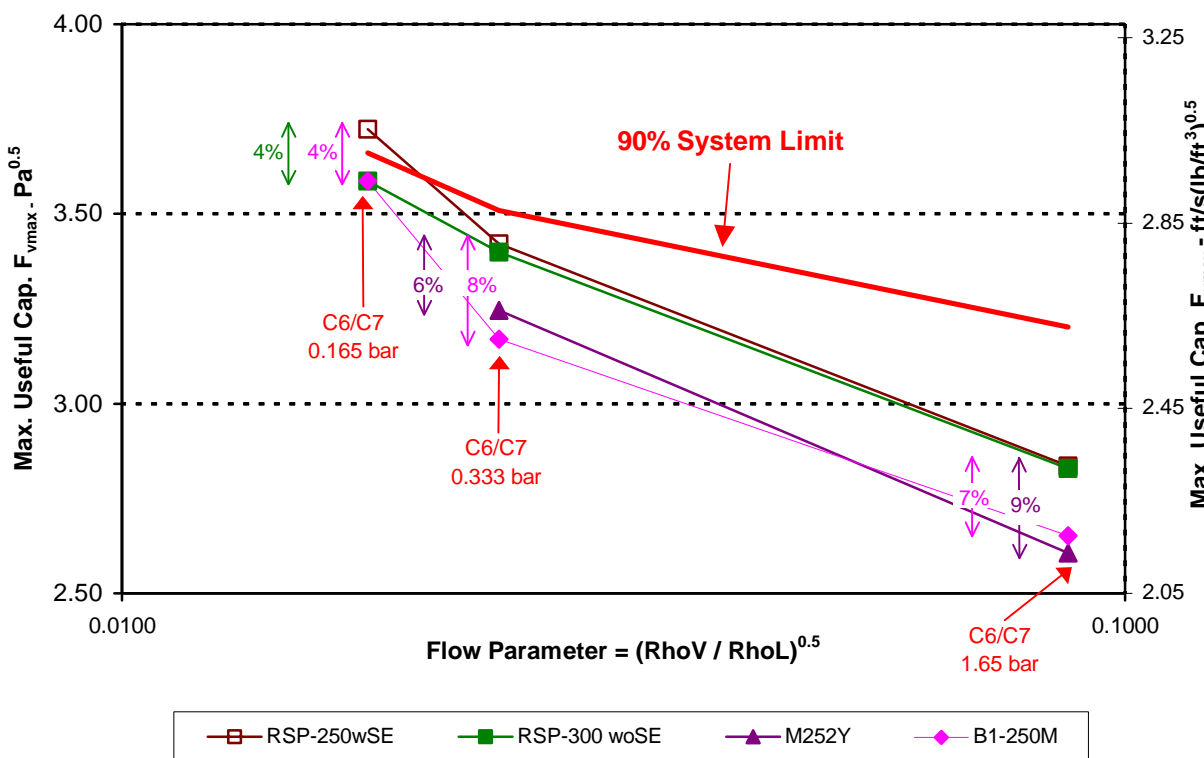


Figure 9. Maximum Useful Capacity based HETP at Different Pressures versus Flow Parameter Comparison. Raschig Super-Pak RSP-250 wSE vs. RSP-300 woSE, And High Capacity B1-250M and M252Y (FRI)

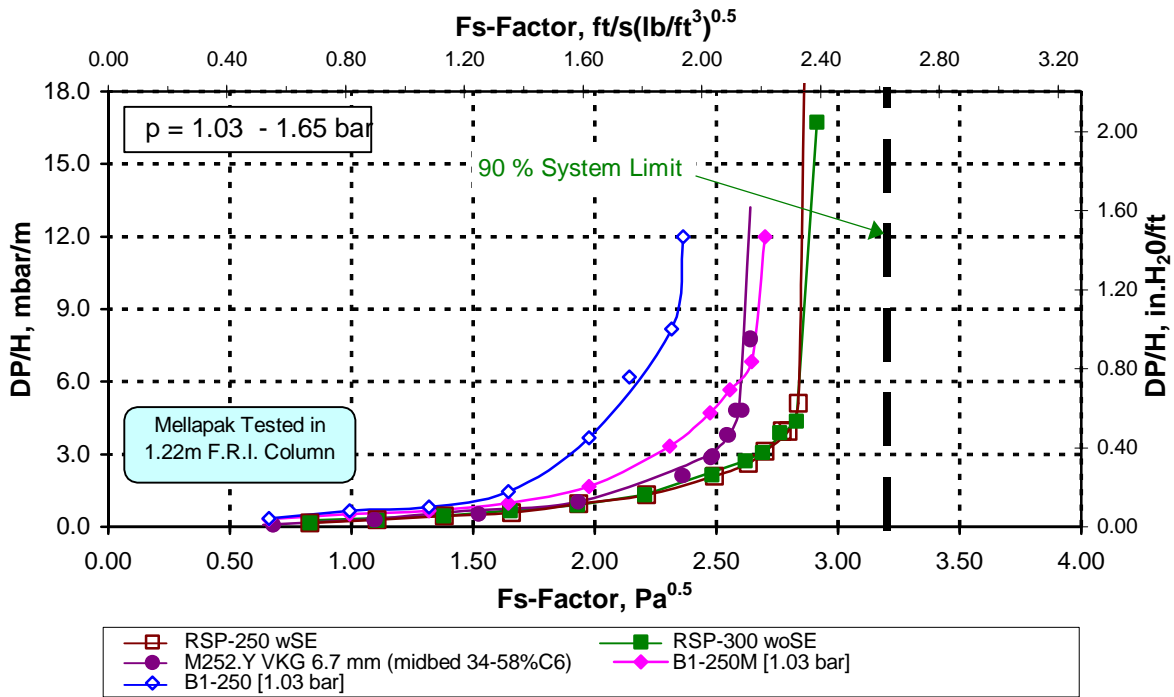


Figure 10. Pressure drop ( $\Delta P/H$ ) comparison at total reflux. Raschig Super-Pak RSP-250 wSE vs. RSP-300 woSE, B1-250, B1-250M and M252Y (FRI), 1.655 bar, 0.43 m I.D. SRP column, 3.05 m bed, C<sub>6</sub>/C<sub>7</sub> system, High capacity distributors

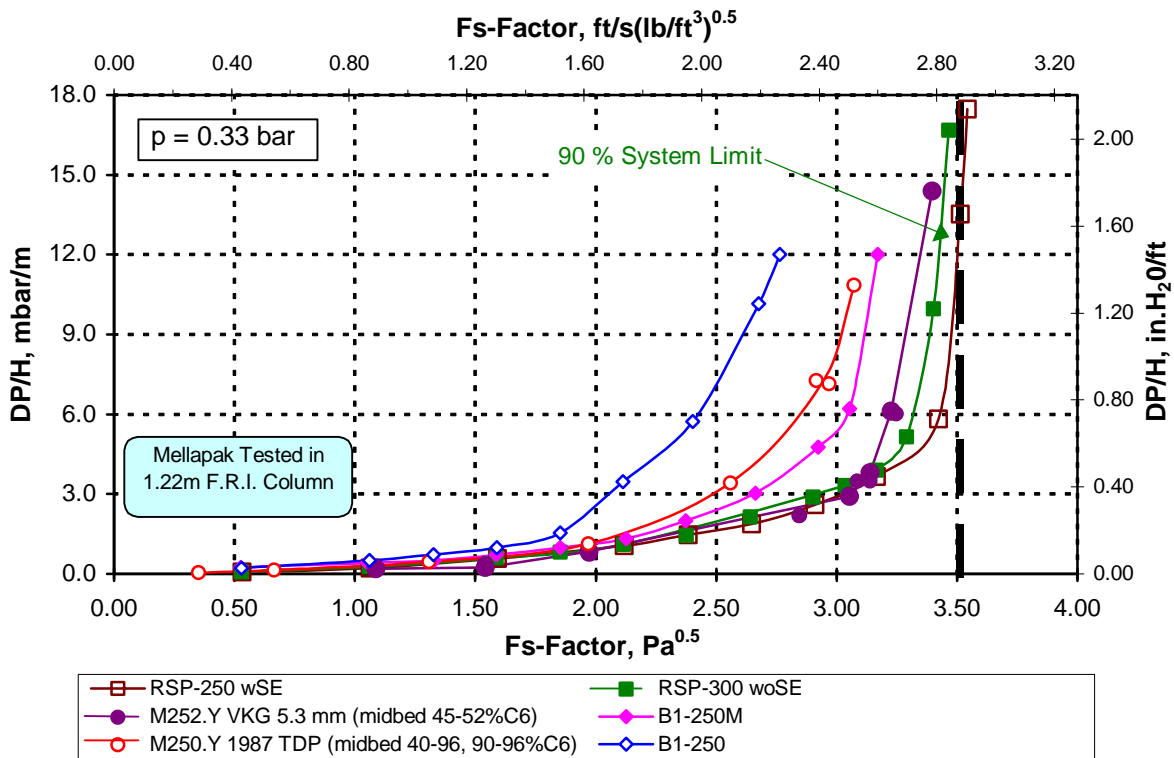


Figure 11. Pressure drop ( $\Delta P/H$ ) comparison at total reflux. Raschig Super-Pak RSP-250 wSE vs. RSP-300 woSE, B1-250, M250Y (FRI 1987), B1-250M and M252Y (FRI), 0.333 bar, 0.43 m I.D. SRP column, 3.05 m bed, C<sub>6</sub>/C<sub>7</sub> system, High capacity distributors

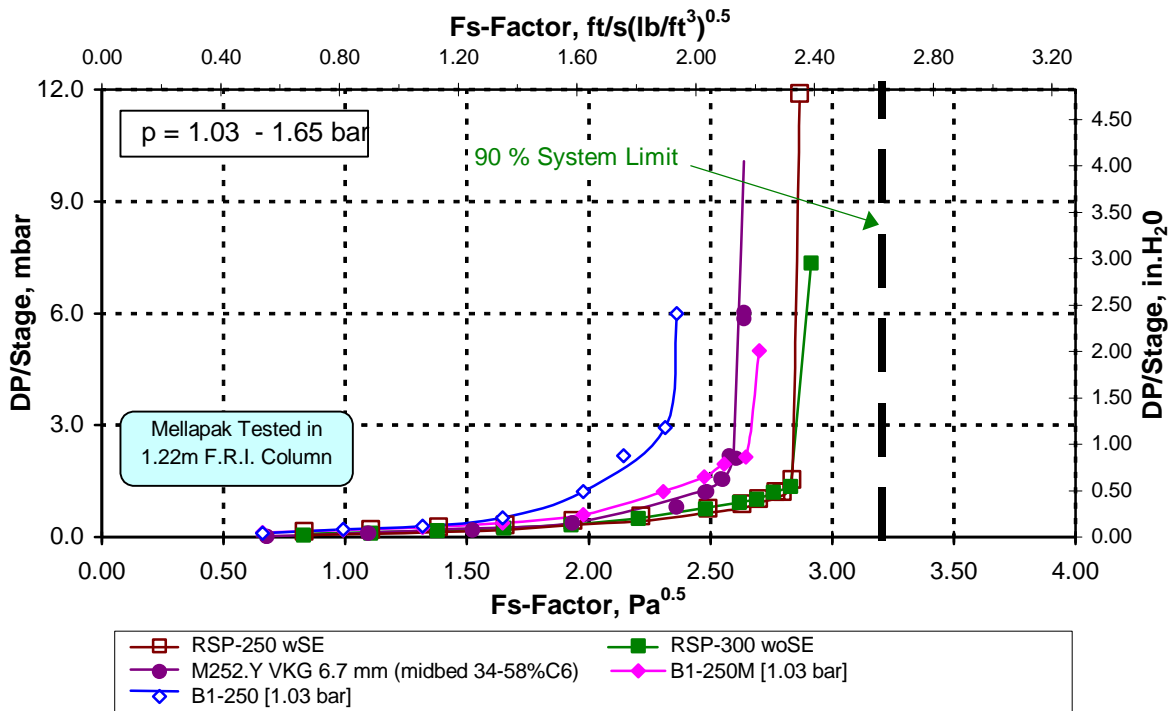


Figure 12. Pressure Drop per Theoretical Stage comparison at total reflux. Raschig Super-Pak RSP-250 wSE vs. RSP-300 woSE, B1-250, B1-250M and M252Y (FRI), 1.655 bar, 0.43 m I.D. SRP column, 3.05 m bed, C<sub>6</sub>/C<sub>7</sub> system, High capacity distributors

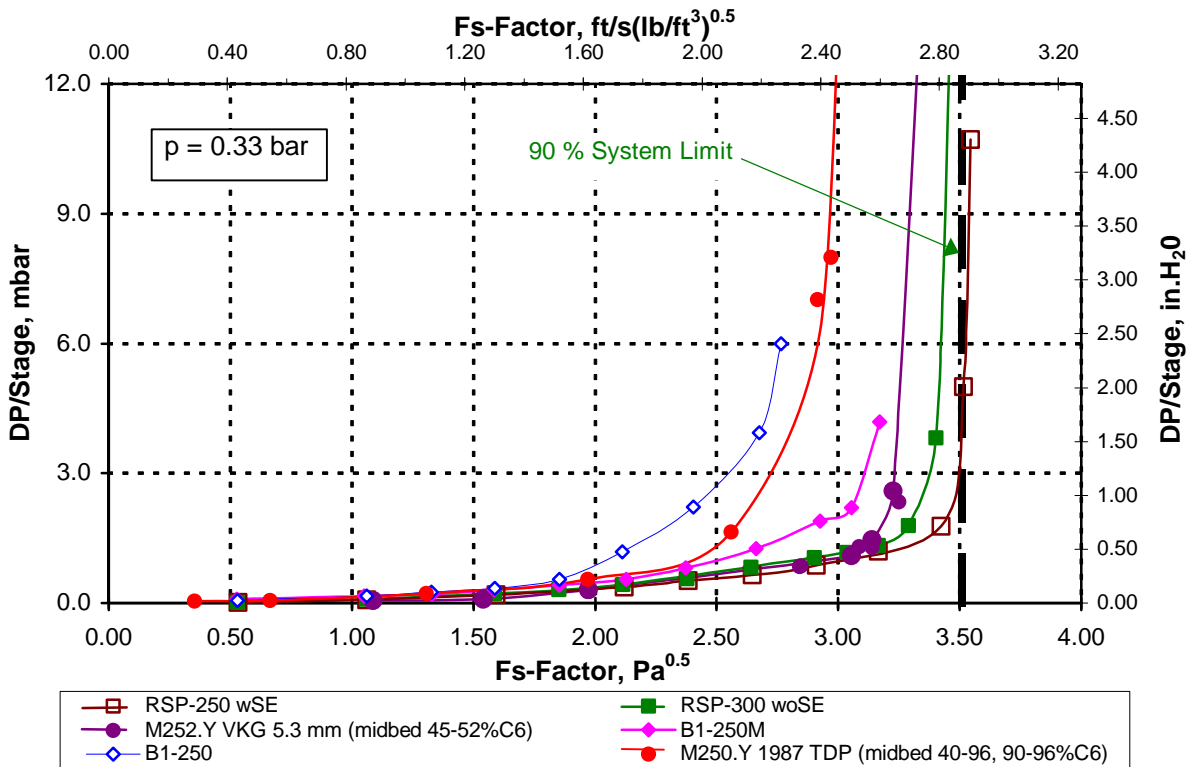


Figure 13. Pressure Drop per Theoretical Stage comparison at total reflux. Raschig Super-Pak RSP-250 wSE vs. RSP-300 woSE, B1-250, M250Y (FRI 1987), B1-250M and M252Y (FRI), 0.333 bar, 0.43 m I.D. SRP column, 3.05 m bed, C<sub>6</sub>/C<sub>7</sub> system, High capacity distributors