

HOW TO SURPASS CONVENTIONAL AND HIGH CAPACITY STRUCTURED PACKINGS WITH RASCHIG SUPER-PAK

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Abstract: Raschig Super-Pak is a novel development in structured packing product technology that is fundamentally different to the well known corrugated perforated or non-perforated, textured sheet metal structured packings. It comprises of a systematic sequence of smooth sinusoidal waves above and below the plain of the metal sheet. Tests at the Ruhr University of Bochum showed that the new open structure resulted in very high capacities low pressure drops and excellent mass transfer efficiencies.

Encouraged by these early successes, total reflux distillation tests with Raschig Super-Pak 300 were conducted at the Separations Research Program, University of Texas at Austin. Results in terms of useful capacity, mass transfer efficiency, pressure drop and pressure drop per theoretical stage are presented. Comparisons with the Montz standard B1-250 and high capacity B1-250M structured packings tested under identical conditions will be shown. In addition results are compared against F.R.I. tested Mellapak M250Y and MellapakPlus M252Y structured packings for the same test fluid at 0.34 and 1.65 bar system pressures. Overall Raschig Super-Pak 300 exhibits higher useful capacities and lower pressure drops compared not only with standard 45° corrugation angle 250 m² m⁻³ surface area structured packings but also with the high capacity counterpart types as well. Remarkably these gains were achieved without any adverse effects on mass transfer efficiency. This observation is reflected in the lower pressure drop per theoretical stage of Raschig Super-Pak 300 compared to the 250 m² m⁻³ surface area structured packings. These highly encouraging results provide industry with an alternative choice for smaller column diameter and/or higher capacity: the Raschig Super-Pak.

Keywords: Raschig Super-Pak; structured packings; distillation; useful capacity; pressure drop.

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DOI: 10.1205/cherd06101

0263-8762/07/
\$30.00 + 0.00

Chemical Engineering
Research and Design

Trans IChemE,
Part A, January 2007

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INTRODUCTION

For the past 25 years, structured packings have gained wide acceptance in the various chemical process industries, from deep vacuum (rectification) up to high pressure (absorption) because of their favourable capacity/low pressure drop/high efficiency characteristics. In response to higher capacity demands, modifications were required to standard structured packings because of initial flooding at the load point. It is well documented in the literature (Spiegel and Meier, 2000; Olujić *et al.*, 2001b; McNulty and Sommerfeld 1999). In brief at the load point, the liquid volume fraction is disproportionately higher at the base of the packing layer interface where adjacent elements touch than in the bulk of packing elements. Combined with increased frictional forces imposed on rising vapour flow, the net result is significant restrictions on the liquid–vapour traffic, which limit increases in capacity. Consequently, a new generation of high capacity structured

packings, 'Mellapakplus[®]', 'Montz-PakM[®]' and 'Flexipac[®]HCTM' were developed. Specific details on how these new structured packing types were developed to increase capacity are explained elsewhere (Spiegel and Meier, 2000; Olujić *et al.*, 2001b, McNulty and Sommerfeld 1999).

Despite the different performance characteristics between standard and high capacity structured packings, they all consist of vertically arranged bundles of corrugated (crimped), thin metal sheets. The most common corrugation angle to the horizontal is 45°, although a 60° angle is typically used when low pressure drop is of concern. Packing vendors use different surface enhancements on the thin metal sheets in an attempt to optimize wetting by use of holes, slots, vanes and tabs and/or lanced, grooved, textured or smooth treatment (Kister, 1992). All methods attempt to improve turbulence within a liquid film, increase available surface area for mass transfer and promote mixing between different parts of the

packing. The most common practice is to perforate individual metal sheets with the belief that it enhances uniform spread of vapour and/or liquid on the front and back of corrugated sheets within a packing layer. However Strigle (1994) states that either liquid or vapour flow through perforations is a very low fraction of the total flow. Furthermore, it has been argued that perforating packing sheets can eliminate up to 10% of available material surface area and potential efficiency. This is supported by experimental evidence with a generic $250 \text{ m}^2 \text{ m}^{-3}$ structured packing in which the efficiency of the perforated version was about 8–10% lower than the non-perforated standard in the low liquid rate region (Olujic *et al.*, 2003).

BACKGROUND

The purpose of this paper is to discuss development of Raschig Super-Pak 300 and how its performance compares with both conventional and high capacity corrugated sheet metal structured packings. Raschig Super-Pak 300 (RSP-300) is a novel development from Raschig GmbH comprising of a systematic sequence of smooth sinusoidal waves above and below the plain of the metal sheet at a 45° angle of orientation as shown in Figure 1. Packing sheets are arranged vertically to form a layer. Production of the first Raschig Super-Pak yielded a surface area of $300 \text{ m}^2 \text{ m}^{-3}$ and is the first in a family of future planned Super-Pak structured packings. RSP-300 has a void fraction of 0.977 and sheet metal thickness is 0.15 mm. Additionally, as a first step, the sinusoidal waves are neither textured nor surface treated. Derived from hydraulic studies, the optimized open geometry deliberately promotes defined turbulent liquid film flows that spread uniformly between the back and front of each metal sheet via numerous contact points; a feature that is open to question with the 'closed' channels in corrugated sheet types. The

wave structure facilitates regular fluid communication on both sides of each packing sheet, thus maximizing surface area for uniform liquid/vapour distribution. This, in addition to lower shear stress forces encountered by countercurrent vapour flow, results in very high capacity low pressure drop and excellent mass transfer performance.

Extensive testing at the University of Texas at Austin and Ruhr University of Bochum with air–water and ammonia–air–water test systems show at least 25% higher capacity and 30% lower pressure drop compared with a conventional corrugated sheet metal structured packing with comparable specific surface area (Raschig Super-Pak 300, 1998). Results are shown in Figures 2 and 3.

TEST UNIT AND EXPERIMENTAL PROCEDURES

Encouraged by these results, the University of Texas at Austin Separations Research Program (SRP) conducted total reflux distillation tests to characterize the new RSP-300 metal structured packing. Hydraulic and mass transfer performance was measured using the cyclohexane/n-heptane (C_6/C_7) test system at operating pressures of 0.165, 0.33, 1.65 and 4.14 bar. Performance of the new RSP-300 structured packing is compared against the B1-250 and B1-250M conventional and high capacity structured packings from Montz tested under identical conditions. These data were taken from the Paper, *Performance Characteristics of a New High Capacity Structured Packing* by Olujic *et al.* (2001a). In addition results are compared against F.R.I. tested Mellapak M250Y and MellapakPlus M252Y structured packings from Sulzer for the C_6/C_7 at 0.34 and 1.65 bar test systems as reported by Pilling and Spiegel (2001).

Distillation tests were performed in the SRP 0.43 m ID column with a bed height of 3.124 m. The liquid distributor

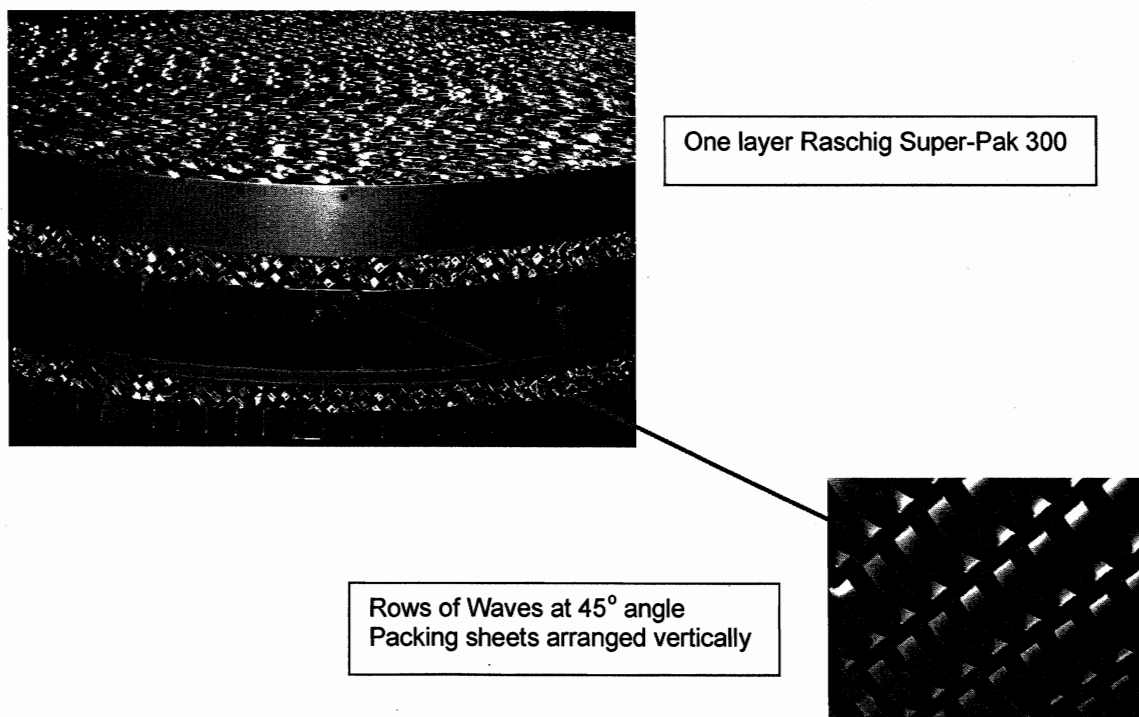


Figure 1. Photographs of segment of Raschig GmbH Raschig Super-Pak 300 structured packing.

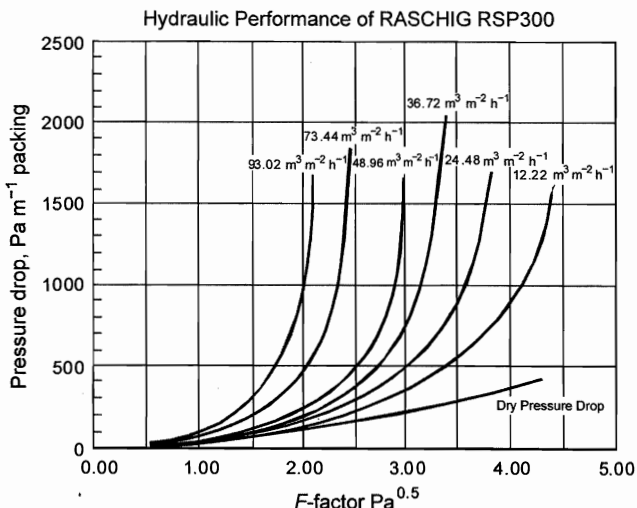


Figure 2. Effect of pressure drop per meter packed height of Raschig Super-Pak 300 with increasing gas capacity factor at constant liquid rates. Column ID 0.43 m, bed height 3.124 m. Air/water tests performed at Separations Research Program, University of Texas at Austin, Texas.

used was the SRP high capacity narrow trough drip tube distributor, with 145 pour points m^{-2} and liquid flow rate range of $5\text{--}50 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$. A complete description of the experimental set up and operating procedures can be found elsewhere (Olujic *et al.*, 2003).

Given the close-to-ideality nature of C_6/C_7 system at total reflux, the Fenske equation is used to calculate the number of equilibrium stages from the distillate and bottoms composition and average relative volatility. The average relative

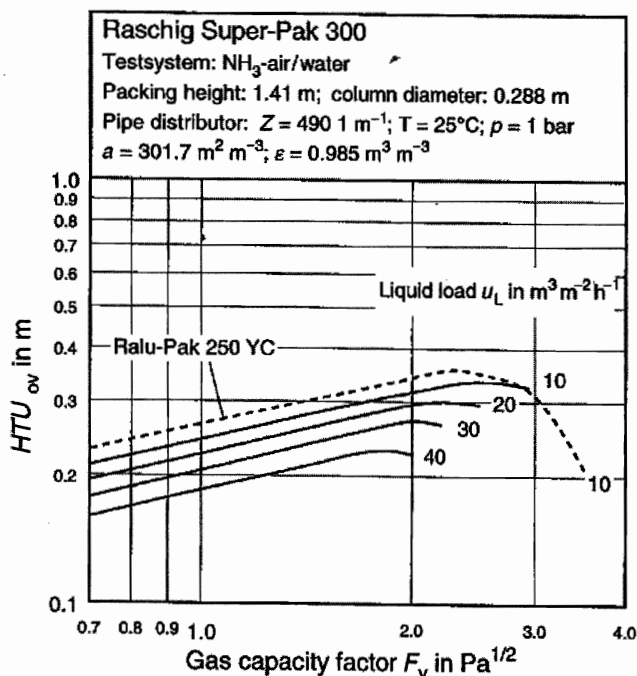


Figure 3. Effect of height of a transfer unit of Raschig Super-Pak 300 with increasing gas capacity factor at constant liquid rates. Column ID 0.288 m, bed height 1.41 m. Ammonia-air-water tests, Ruhr University, Bochum, Germany.

Table 1. Physical properties of the cyclohexane/n-heptane, C_6/C_7 system (average at column bottom conditions) at four system pressures used in total reflux tests.

Pressure (bar)	0.165	0.33	1.65	4.14
Liquid density, kg m^{-3}	659	656	608	560
Liquid viscosity, mPa s	4.5E-1	4.3E-1	2.3E-1	1.6E-1
Liquid diffusivity, $\text{m}^2 \text{ s}^{-1}$	2.29E-9	2.73E-9	6.19E-9	9.16E-9
Vapour density, kg m^{-3}	0.65	1.18	5.44	13.1
Vapour viscosity, mPa s	6.6E-3	7.0E-3	8.3E-3	9.1E-3
Vapour diffusivity, $\text{m}^2 \text{ s}^{-1}$	13.4E-6	11.3E-6	2.94E-6	1.42E-6
Surface tension, mN m^{-1}	18	17	14	8
Relative volatility	1.96	1.80	1.57	1.42
Average temperature, $^{\circ}\text{C}$	49	61	114	152

volatilities of the C_6/C_7 mixture together with various physical property values at the four operating pressures are given in Table 1.

It should be noted that the RSP-300 and Montz structured packing (Olujic *et al.*, 2001a) experimental data were obtained using the SRP State-of-the-Art Fisher-Rosemount advanced process control and data acquisition system. This permits like-for-like comparisons.

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

RESULTS AND DISCUSSION

Liquid Rate and Operating Pressure Effect on Efficiency

Figure 4 shows good and stable HETP values for RSP-300 at all four operating pressures over almost the entire liquid rate range of the high capacity liquid distributor. With each operating pressure, HETP reaches a constant value in the preloading regime. In the loading regime there is a pronounced decline 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. It can be seen the HETP is generally between 0.305 and 0.41 m regardless of pressure.

At 4.14 bar system pressure and liquid rate of $48.7 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$, typical of high pressure distillation, there was no 'efficiency hump', a phenomenon observed with both conventional and high capacity structured packings (Olujic *et al.*, 2001a; Stupin and Kister, 2003). The result is remarkable given that the flow channels in adjacent RSP-300 packing layers are at 90° with respect to one another when vertically stacked. The open structure helps alleviate any restrictions in vapour-liquid flows at the layer interface and possible vapour backmixing that otherwise may be found in the more closed channels of corrugated sheet structured packings.

Figure 4 has superimposed on it the 90% System Limit, based on published correlation and 'System Limit' data (Stupin and Kister, 2003), for each of the four operating pressures and will set a precedent for the remaining figures below. At higher pressures, the rise in RSP-300 HETP at flow rates close to hydraulic flood occurs long before the 90% System Limit is reached. This is clearly shown with

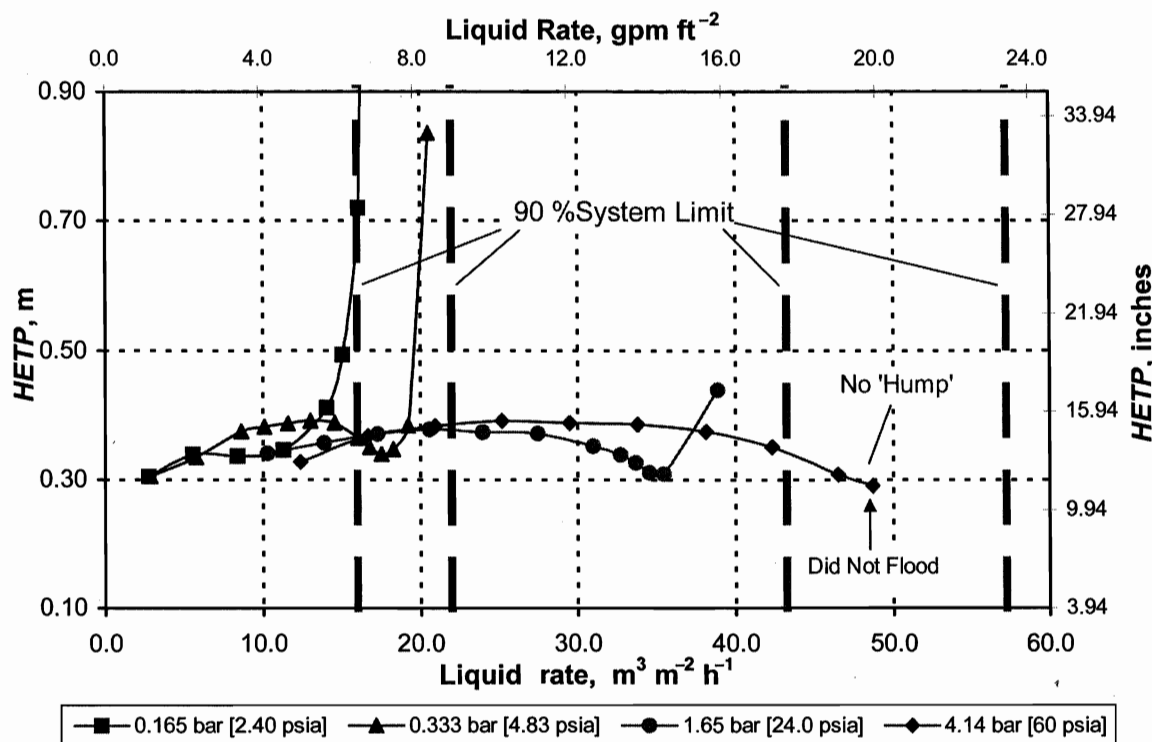


Figure 4. Effect of liquid rate and operating pressure on Raschig Super-Pak 300 HETP at total reflux 0.43 m I.D. SRP Column, 3.124 m bed, C6/C7 system, high capacity distributor with drip tubes.

1.65 bar pressure. With 4.14 bar pressure, the rise in RSP-300 HETP at hydraulic flood would have occurred long before the 90% System Limit had the reboiler not reached its capacity limit. With decreasing pressure, the rise in the RSP-300 HETP curve at flow rates close to hydraulic flood converge and rapidly approach the 90% System Limit until a critical point is reached where it crosses the 90% limit. This is illustrated with 0.165 bar pressure in Figure 4. Overall, it implies that at lower operating pressures, there is a higher tendency of high performance structured packings such as Raschig Super-Pak to rapidly approach 90% System Limit before it enters full hydraulic flood.

Efficiency and Useful Capacity

Capacity-efficiency comparative plots of RSP-300 with B1-250 and B1-250M structured packings, taken from the paper *Performance of a New High Capacity Structured Packing* (Olujic *et al.*, 2001a), are presented in Figures 5 and 6 with the C₆/C₇ at 1.65 and 0.33 bar test systems. RSP-300 hydraulic and mass transfer data at 1.65 bar operating 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 Figure 5 the HETP in the mid-capacity range at 1.65 bar pressure for RSP-300 is 0.375 m compared to 0.36 m and 0.39 m for the B1-250 and B1-250M, respectively. At 0.33 bar, Figure 6 shows an HETP of 0.38 m for RSP-300 in the mid-capacity range compared to 0.36 m for B1-250 and 0.41 m for B1-250M.

For both operating pressures, RSP-300 shows both a distinct minimum in HETP, and a clear maximum useful capacity advantage (defined as the last point on the HETP curve at which preloading efficiency is still achieved) compared with

B1-250. At 1.65 bar, Figure 5 shows a maximum useful capacity advantage of 22% for RSP-300 compared with B1-250 and more significantly 6% over the high capacity B1-250M. Had B1-250 and B1-250M been tested at 1.65 bar the useful capacity advantages may have been greater. Similarly at 0.33 bar in Figure 6, the RSP-300 useful capacity advantage is 27% compared to B1-250 and 8% over B1-250M.

Figures 7 and 8 compare HETP of RSP-300 with F.R.I. tested Mellapak M250Y (Fitz *et al.*, 1999; Pilling and Spiegel, 2001) and high capacity MellapakPlus M252Y (Pilling and Spiegel, 2001). Both plots utilize Cs-Factors based on column bottom conditions and mid-bed C₆ composition range except for M250Y since insufficient data were available in the original tests to calculate Cs from bottom column conditions. With this in mind, the HETP in the mid capacity range for M250Y and M252Y at 1.65 bar (Figure 7) are 0.39 m and 0.35 m, respectively compared to the RSP-300 HETP of 0.375 m. At 0.33 bar, the HETP in the mid capacity range for M250Y and M252Y are 0.48 m and 0.37 m, respectively compared with the RSP-300 HETP of 0.38 m as shown in Figure 8. As with the B1-250 packing, RSP-300 displays a substantial maximum useful capacity advantage compared with M250Y. This is illustrated in Figures 7 and 8 with maximum useful capacity advantages of 26% and 34% for RSP-300 compared with M250Y at the respective operating pressures of 1.65 and 0.33 bar. When compared against the high capacity M252Y, the useful capacity gains of RSP-300 at 1.65 and 0.33 bar are 10% and 6% respectively; a significant result. All HETPs and useful capacities are summarized in Table 2 where B1-250 is taken as a reference point set at 100% for a given liquid and vapour rate, against which all the other packings are compared.

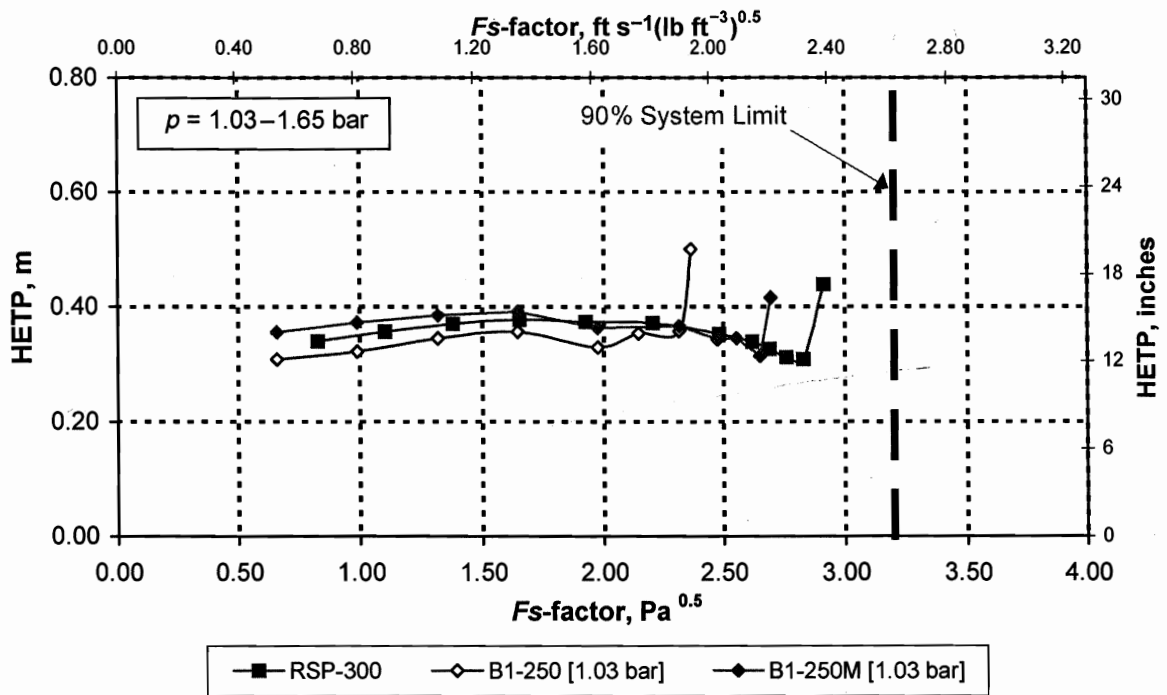


Figure 5. Mass transfer efficiency (HETP) comparison at total reflux. Raschig Super-Pak 300 at 1.65 bar versus B1-250 and B1-250M at 1.03 bar, 0.43 m I.D. SRP column, 3.124 m bed, C₆/C₇ system, high capacity distributor with drip tubes.

The useful capacity advantage of RSP-300 over the high capacity B1-250M and M252Y structured packings is remarkable given that the flow channels in adjacent RSP-300 packing layers are at 90° with respect to one another when vertically stacked. The open structure of Raschig Super-Pak alleviates any restrictions in vapour-liquid flows at the element interface where layers touch.

Hydraulic-Pressure Drop Comparison

Pressure drop comparative plots of RSP-300 with B1-250 and B1-250M packings are presented in Figures 9 and 10 for 1.65 and 0.33 bar operating pressures. For both system pressures RSP-300 pressure drop is considerably lower than both the B1-250 and B1-250M structured packing over

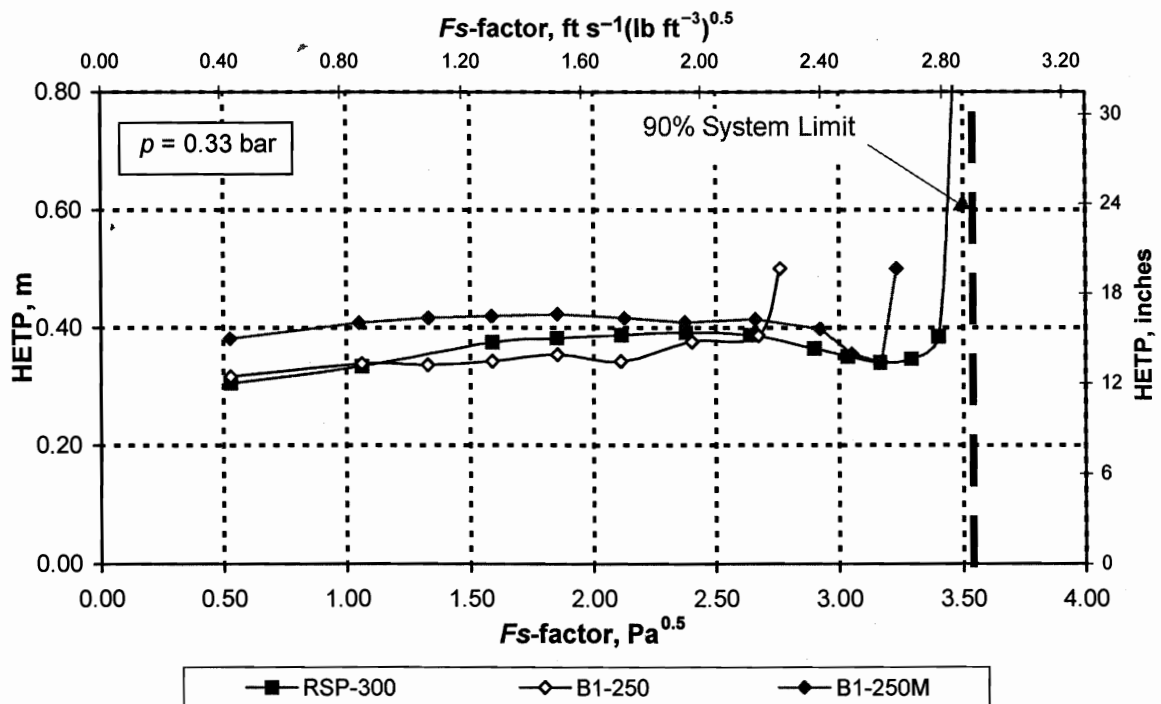


Figure 6. Mass transfer efficiency (HETP) comparison at total reflux. Raschig Super-Pak 300 versus B1-250 and B1-250M at 0.33 bar, 0.43 m I.D. SRP column, 3.124 m bed, C₆/C₇ system, high capacity distributor with drip tubes.

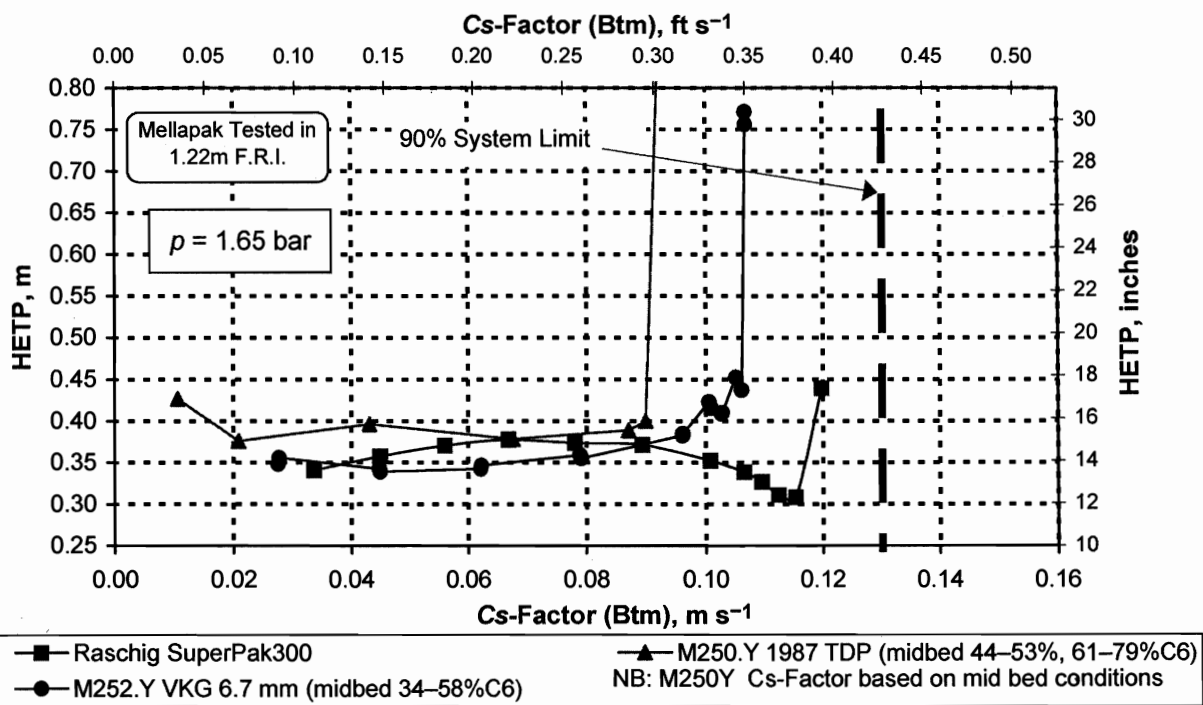


Figure 7. Mass transfer efficiency (HETP) comparison at total reflux. Raschig Super-Pak 300 versus F.R.I. tested M250Y and M252Y at 1.65 bar, 0.43 m I.D. SRP column, 1.22m F.R.I. column, C_6/C_7 system, high capacity liquid distributors.

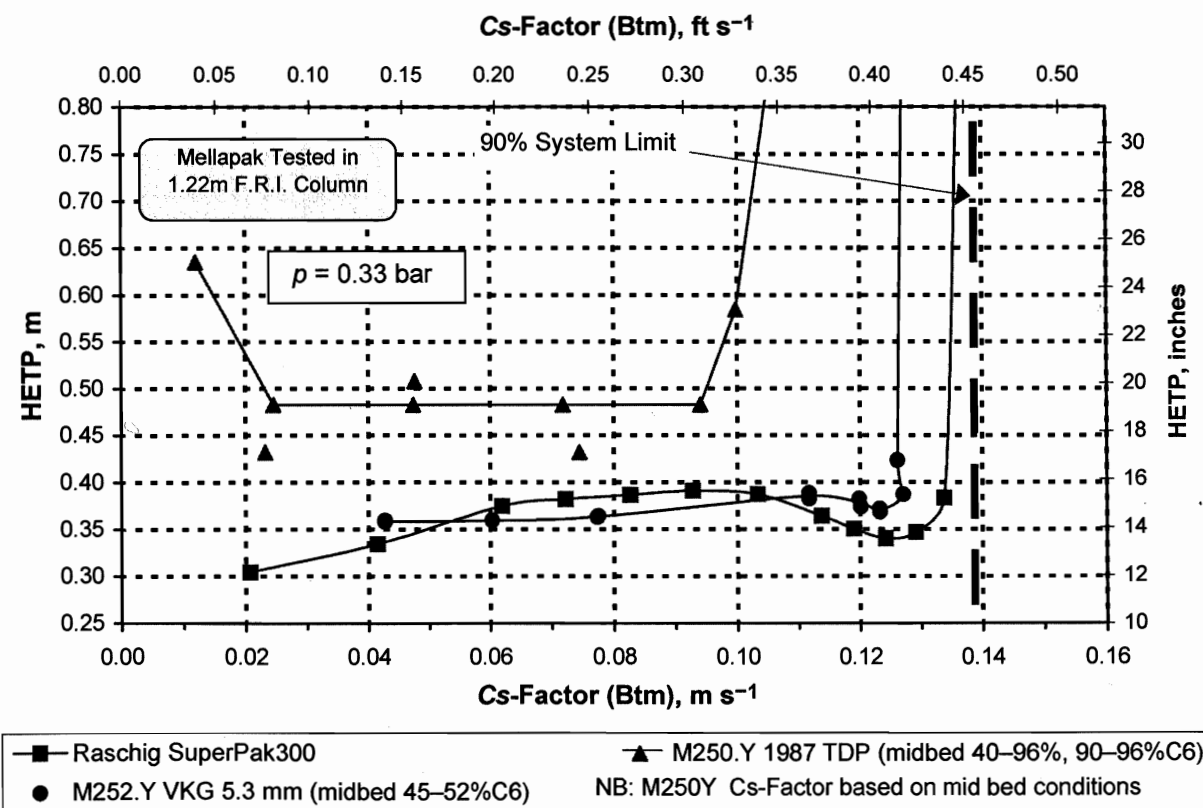


Figure 8. Mass transfer efficiency (HETP) comparison at total reflux. Raschig Super-Pak 300 versus F.R.I. tested M250Y and M252Y at 0.33 bar, 0.43 m I.D. SRP column, 1.22 m F.R.I. column, C_6/C_7 system, high capacity liquid distributors.

Table 2. Maximum useful capacity comparison Raschig Super-Pak 300 versus B1-250, M250Y, standard and B1-250M and M252Y high capacity structured packings at total reflux conditions with C_6/C_7 system.

Pressure p [bar]	Standard packing		High capacity packing		Ultimate packing
	Montz B1-250	¥ Sulzer M250 Y	Montz 1-250 M	¥ Sulzer M252 Y	Raschig RSP 300
1.650	—	98%	—	112%	123%
1.03*	100%	—	115%	—	—
0.333	100%	95%	118%	120%	127%

*Montz B1-250 and B1-250M tested at 1.03 bar (Olujic *et al.*, 2001a) not 1.65 bar.

¥ Extracted from data reported by Pilling and Spiegel (2001).

M250Y F_s -factors based on mid bed conditions since no data reported in original tests to calculate F_s based on column bottom conditions.

the entire operating range. At the lower operating pressure of 0.33 bar, the ΔP curve at maximum useful capacity for RSP-300 is very close to or at the 90% System Limit. Also the pressure drop curves show the capacity advantage of RSP-300 against Montz standard and high capacity types. Had B1-250 and B1-250M been tested at 1.65 bar the useful capacity advantages may have been greater.

Figures 11 and 12 compare pressure drop of RSP-300 with M250Y and M252Y at 1.65 to 0.33 bar operating pressures. As with the HETP plots, C_s -factors based on column bottom conditions and mid-bed C_6 composition range have been utilized except for M250.Y for reasons given above.

Additionally no pressure drop data were reported at 1.65 bar for M250Y test in 1987. The convergence of maximum useful capacity of both RSP-300 and M252Y at the lower pressure, suggests that the on-set of hydraulic film flooding is very close to or at the 90% System Limit for both packings. At 1.65 bar RSP-300 has a more pronounced useful capacity advantage of 9% over the high capacity M252Y; a remarkable result. The pressure drop curve of Sulzer's high capacity structured packing M252Y runs much more in line with RSP 300 than the Montz type high capacity structured packing 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 RSP-300 had been tested at SRP.

Pressure Drop per Theoretical Stage Comparison

With structured packing applications there is a trade-off between capacity and efficiency. As a result, pressure drop per theoretical stage is an important parameter in evaluating different structured packing designs. Figures 13 and 14 show pressure drop per theoretical stage comparisons of RSP-300 with B1-250 and 250M standard and high capacity structured packings at 1.65 and 0.33 bar operating pressures. Likewise Figures 15 and 16 show pressure drop per theoretical stage comparisons of RSP-300 with M250Y and M252Y. For both pressures, the pressure drops per theoretical stage of RSP-300 is consistently and distinctly lower than the B1-250 and B1-250M in Figures 13 and 14. In Figures 15 and 16, RSP-300 shows a noticeably lower pressure drop per theoretical stage over M250Y and

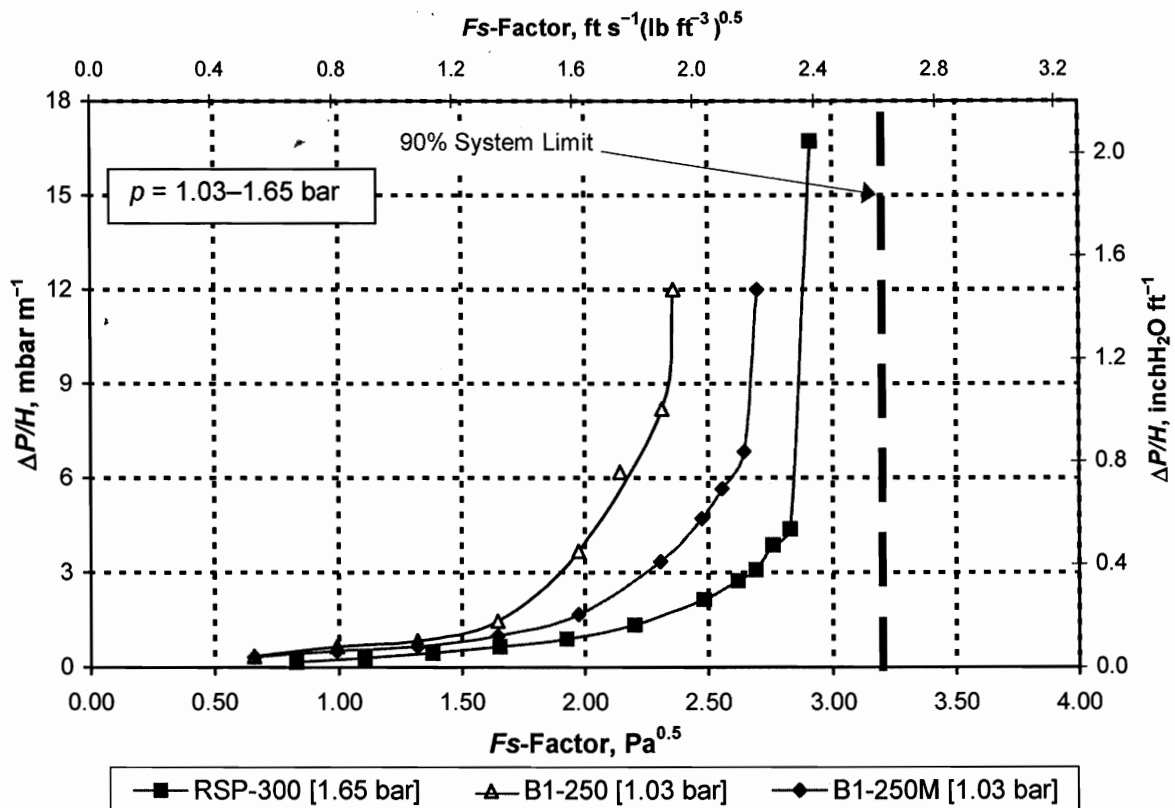


Figure 9. Pressure drop comparison at total reflux. Raschig Super-Pak300 at 1.65 bar versus B1-250 and B1-250M at 1.03 bar, 0.43 m I.D. SRP column, 3.124 m bed, C_6/C_7 system, high capacity distributor with drip tubes.

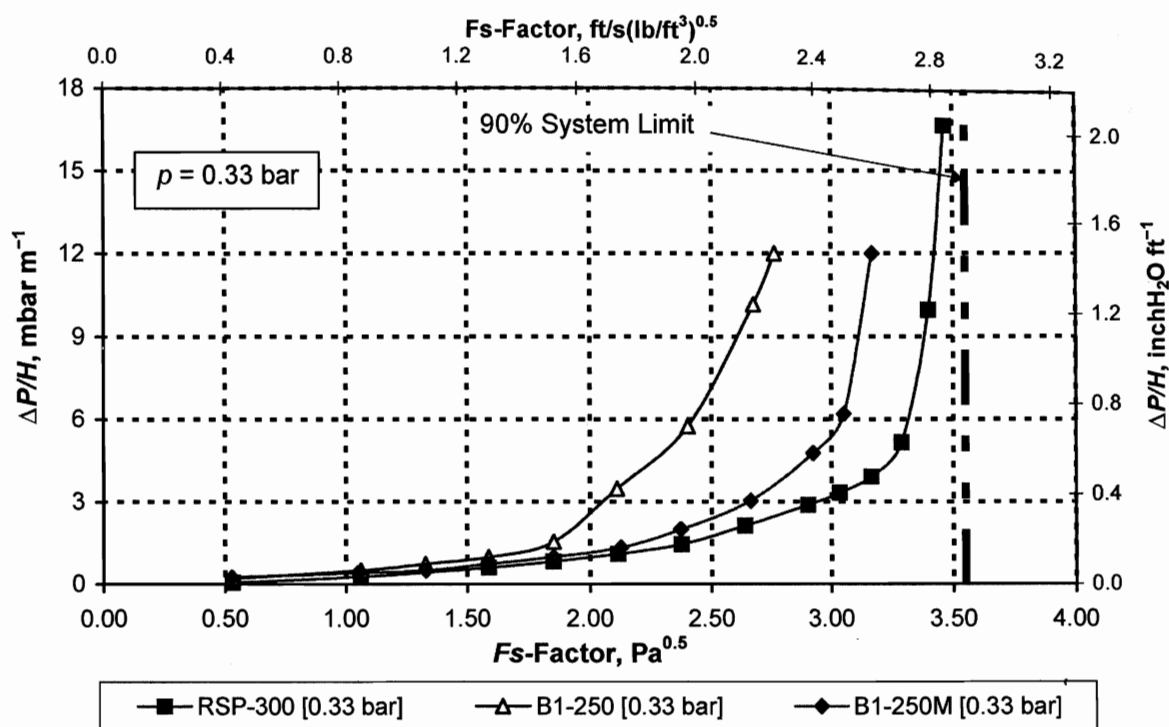


Figure 10. Pressure drop comparison at total reflux. Raschig Super-Pak300 versus B1-250 and B1-250M at 0.33 bar, 0.43 m I.D. SRP column, 3.124 m bed, C_6/C_7 system, high capacity distributor with drip tubes.

M252Y in the high capacity operating range for both operating pressures. These results are very favourable in low pressure and vacuum columns processing thermally sensitive fluids.

On the whole, the excellent hydraulic advantages of RSP-300 over the B1-250M and M252Y high capacity structured packings is remarkable given that adjacent Raschig Super-Pak 300 layers are rotated 90° with respect to one another.

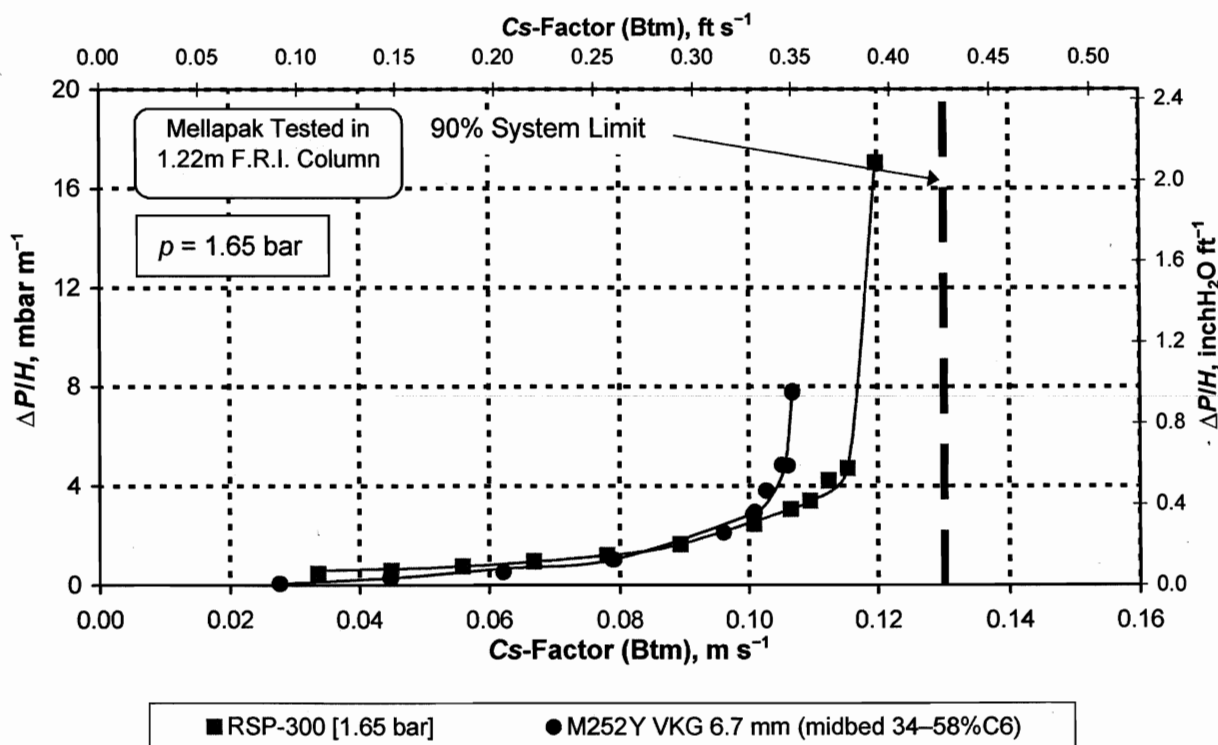


Figure 11. Pressure drop ($\Delta P/H$) comparison at total reflux. Raschig Super-Pak300 versus F.R.I. tested M252Y at 1.65 bar, 0.43 m I.D. SRP column, 1.22 m F.R.I. column, C_6/C_7 system, high capacity liquid distributors.

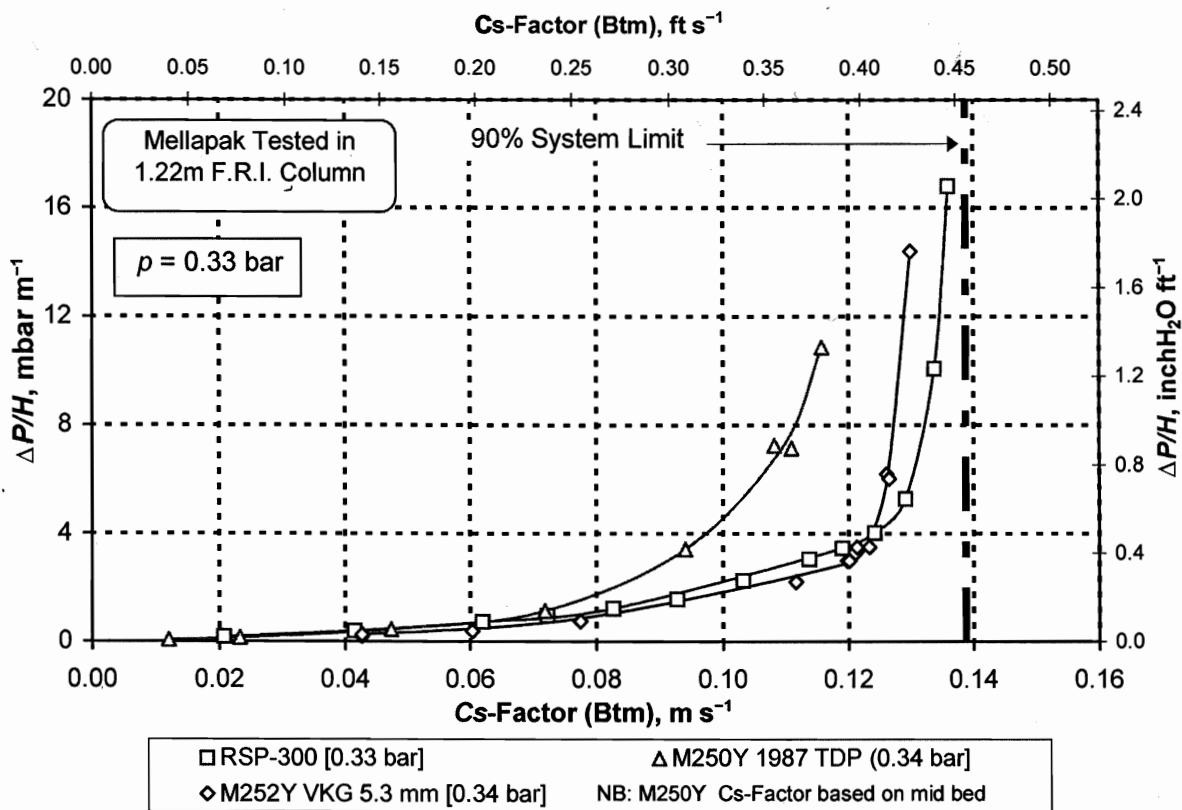


Figure 12. Pressure drop ($\Delta P/H$) comparison at total reflux. Raschig Super-Pak300 versus F.R.I. tested M250Y and M252Y at 0.33 bar, 0.43 m I.D. SRP column, 1.22 m F.R.I. column, C_6/C_7 system, high capacity liquid distributors.

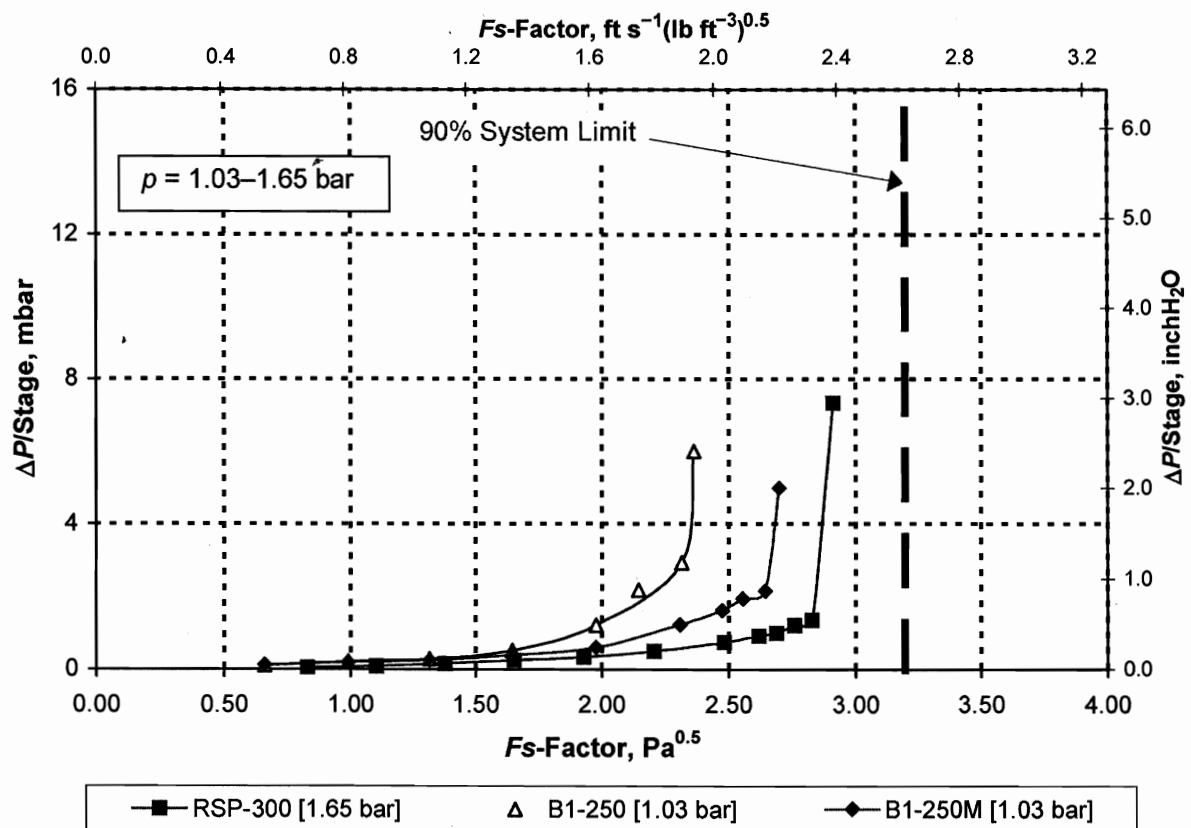


Figure 13. Pressure drop per theoretical stage comparison at total reflux. Raschig Super-Pak300 at 1.65 bar versus B1-250 and B1-250 M at 1.03 bar, 0.43 m I.D. SRP column, 3.124 m bed, C_6/C_7 system.

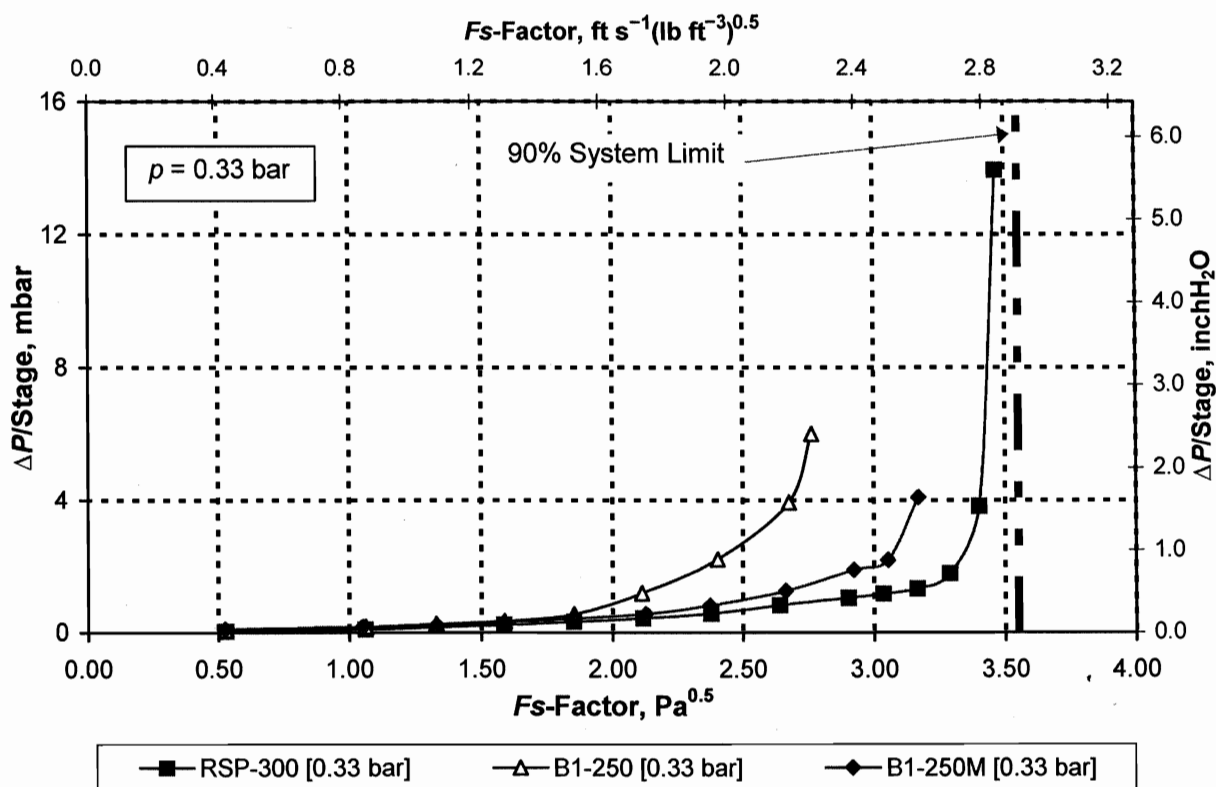


Figure 14. Pressure drop per theoretical stage comparison at total reflux. Raschig Super-Pak300 versus B1-250 and B1-250 M at 0.33 bar, 0.43 m I.D. SRP column, 3.124 m bed, C_6/C_7 system.

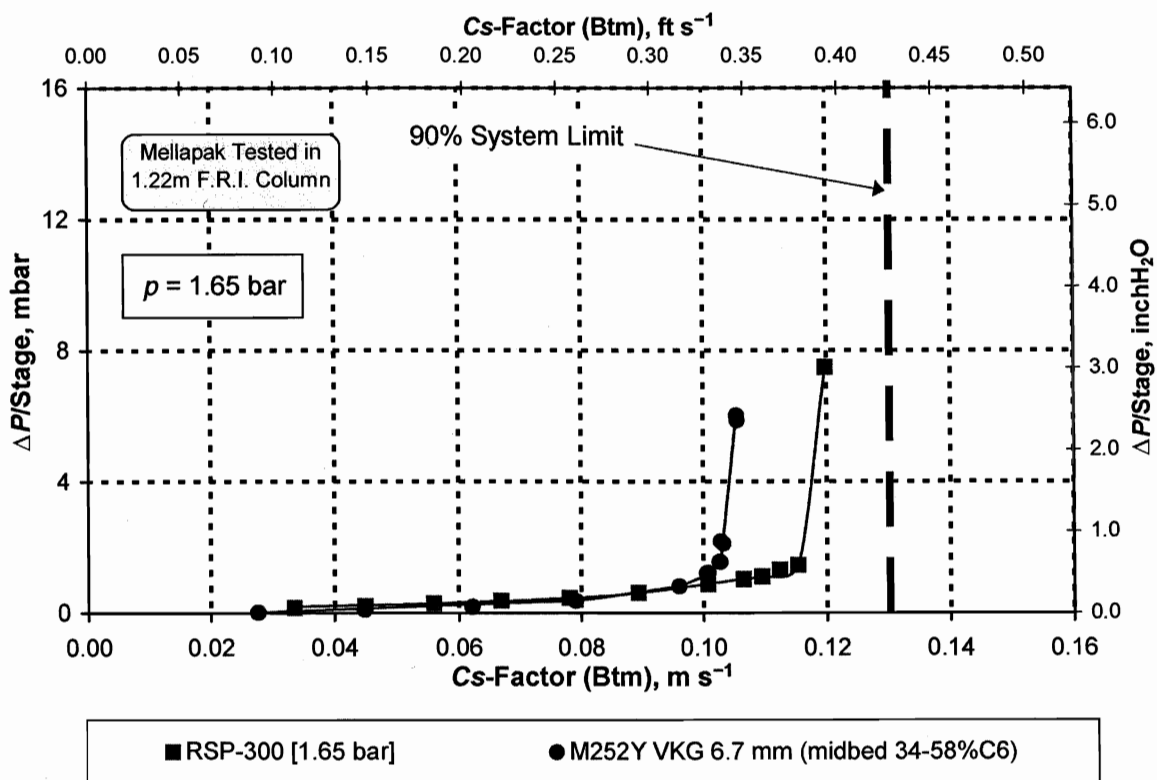


Figure 15. Pressure drop per theoretical stage comparison at total reflux. Raschig Super-Pak300 versus F.R.I. tested M252Y at 1.65 bar, 0.43 m I.D. SRP column, 1.22 m F.R.I. column, C_6/C_7 system.

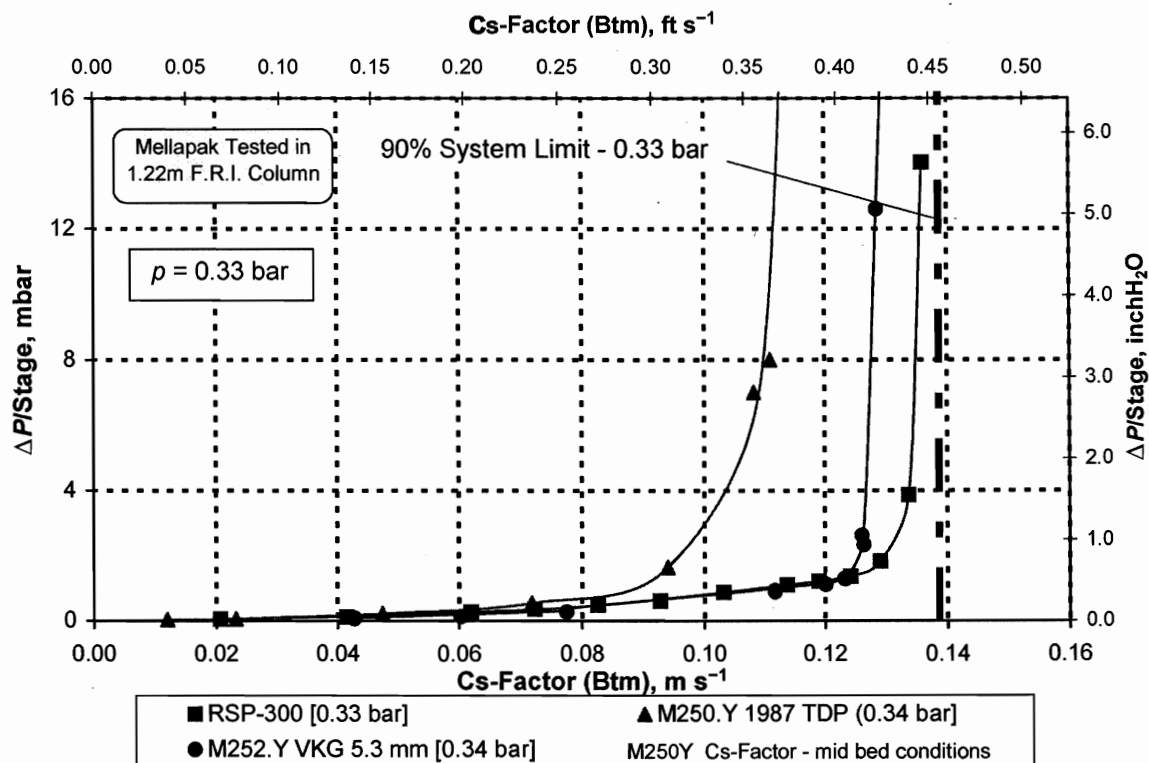


Figure 16. Pressure drop per theoretical stage comparison at total reflux. Raschig Super-Pak300 versus F.R.I. tested M250Y and M252Y at 0.33 bar, 0.43 m I.D. SRP column, 1.22 m F.R.I. column, C_6/C_7 system.

This is in contrast to the B1-250M and M252Y high capacity types with curvature of the corrugations gradually changing from 45° to 0° on vertical axis at one or both ends of the packing elements.

CONCLUSIONS

The novel design of Raschig Super-Pak 300 structured packing offers the various chemical process industries an alternate choice over the well known corrugated sheet metal conventional and high capacity structured packings. The open structure results in excellent hydraulic and mass transfer efficiency characteristics as verified in the total reflux distillation tests at the Separations Research Program (SRP), University of Texas at Austin. Significant useful capacity and low pressure drop advantages were obtained not only over the standard B1-250 and M250Y structured packings but over the B1-250M and M252Y high capacity structured packings as well. Equally important is that mass transfer efficiency was at least as good as the 250 m² m⁻³ surface area structured packings. At low operating pressures, the convergence of hydraulic performance of the high capacity structured packings with that of RSP-300, suggests that the onset of hydraulic flood is very close to or at 90% System Limit. This was not observed at higher operating pressures of 1.65 bar and above. The very encouraging hydraulic advantages of RSP-300 over the B1-250M and M252Y high capacity structured packings is remarkable given that adjacent Raschig Super-Pak 300 layers are rotated 90° with respect to one another like standard structured packings. This contrasts with the gradually changing corrugation angle from 45° to 0° in the vertical axis, which

characterises the B1-250M and M252Y high capacity structured packings. The advantages for RSP-300 are that in new column design the required diameter will decrease though an increase in the capacity of the packing providing the mass transfer efficiency remains constant. Alternatively debottlenecking an existing column to boost throughput capacity can be achieved by replacing the existing packing with ultimate capacity packing: the Raschig Super-Pak.

NOMENCLATURE

C_6	cyclohexane
C_7	n-heptane
C_s	gas or vapour capacity factor = $F_s / \sqrt{\rho_L - \rho_V}$, m s ⁻¹
F_s	gas or vapour capacity factor = $u_s \cdot \sqrt{\rho_V}$, $\sqrt{\text{Pa}}$ or m s ⁻¹ (kg m ⁻³) ^{1/2}
H	packing height, m
HETP	height equivalent to a theoretical stage, m
L	liquid mass flow rate, kg h ⁻¹
p	operating/system pressure, bar
u_L	superficial liquid velocity, m ³ m ⁻² h ⁻¹
u_s	superficial vapour velocity, m s ⁻¹
V	gas or vapour mass flow rate, kg h ⁻¹

Greek Symbols

ΔP	pressure drop, Pa, mbar
ρ_L	liquid density, kg m ⁻³
ρ_V	gas or vapour density, kg m ⁻³

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s	superficial
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ACKNOWLEDGEMENTS

The authors would like to acknowledge the efforts of Professor Jim Fair, Dr Frank Seibert, Mr Christopher Lewis and the SRP staff for their excellent work on the Raschig Super-Pak 300 testing programme.

The manuscript was received 14 July 2006 and accepted for publication after revision 10 November 2006.