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COMMERCIAL SCALE TEST VALIDATION OF MODERN HIGH PERFORMANCE RANDOM AND STRUCTURED PACKINGS FOR CO_2-CAPTURE RANKING

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Abstract
To meet the goal of optimized CO_2-Capture performance from Power Plant flue gas, high capacity/high mass-transfer-efficiency/low pressure drop modern packings are required. To support this claim, hydraulics-efficiency research from Total Reflux Distillation tests in the Commercial/Pilot Test Columns at Fractionation Research Incorporated (F.R.I.) and at the Separations Research Program (SRP) was performed. Additional research to measure pressure drop with the air-water system and mass transfer measurements from CO_2 absorption supplement the findings from distillation testing.. The results show distinct performance advantages of modern high performance metal random and structured packings over the current state-of-the-art packings. The data presented will validate the necessity of such test campaigns so as to rank packings most suitable in CO_2 Absorption/Stripping processes. The packings involved in the comparison studies are Raschig Super-Ring® random packings, various sized Pall Rings® and Third Generation random packings; Raschig Super-Pak® structured packings, Sulzer Mellapak® including Mellapak-Plus®, and the Montz B1® packing types.

Keywords: CO_2-Capture, Commercial/Pilot Test Columns, Distillation, Effective Surface Area

1. Introduction
The use of a chemical absorption/stripping process downstream of power plants is the only mature unit operation available for efficient CO_2 removal. Alkanolamines such as aqueous MEA or MDEA are the most common solvents used for removing CO_2[1]. The problem is high operating costs of the steam necessary for solvent regeneration. As a result interest is very high to improve the process design and operation. To address the above points of interest, computer models/simulations have often been used to study random and structured packing performance. Computer model/simulation results are hard to prove which is why the most practical approach is through pilot plant testing to characterize performance of both solvents and column internals under industrial operating conditions.

Owing to the need for high effective surface area to reduce the Absorber size and low pressure drop to reduce energy consumption, the purpose of this paper is to characterize the performance of modern random and modern structured packings against published data for traditional packings. Evaluation of existing design concepts will form the basis of why new approaches were necessary to develop a high performance random and structured packing. Explanations below will be supported with representative charts from the various Raschig-Jaeger distillation and hydraulic test campaigns. Tests to characterize hydraulic-efficiency performance are summarized in Table 1. The following sections describe the generations of the most popular random and structured packings available on the market as depicted in Figures 1 and 2.

2. Development of Random Packings
Random packing geometries can be classified into three generations as shown in Figure 1. The first two generations are basically rings and saddle shapes, including the Pall Ring, and Intalox Saddle. The most common Third Generation Random Packings are the CMR®, Nutter-Ring®, and IMTP®. The CMR® is an improved geometrical shape of the Pall Ring®, while the Nutter-Ring® and IMTP® are hybrid ring/saddle shapes that exploit the ring feature for mass transfer and the saddle shape for lower pressure drop. In general, most random packings have tongues that deliberately promote drops with

the belief that a higher mass transfer rate will result. While the drops surfaces provide high surface area to mass transfer the bulk liquid inside the drop has low turbulence. In addition drops filling the void space within packing elements provide resistance drag to the rising gas flow causing high pressure drop. Last but not least at higher rates, drops entrain much sooner than film-flows leading to low throughput capacity.

Table 1. Distillation and Air-Water Hydraulic Test Campaigns for various Raschig Super-Pak Structured and Raschig Super-Ring Random Packings

Packing	Test	Test Facility	System	Pressure, bar	Property Measured
RSP-200	Distillation	SRP, ϕ=0.43 m	C6/C7	0.165, 0.33, 1.65, 4.14	Capacity, HETP, ΔP/H
RSP-250	Distillation	SRP, ϕ=0.43 m	C6/C7	0.165, 0.33, 1.65, 4.14	Capacity, HETP, ΔP/H
RSP-350	Distillation	SRP, ϕ=0.43 m	C6/C7	0.165, 0.33, 1.65, 4.14	Capacity, HETP, ΔP/H
RSR #0.5	Distillation	SRP, ϕ=0.43 m	C6/C7	0.165, 0.33, 1.65, 4.14	Capacity, HETP, ΔP/H
RSP-250	Distillation	FRI, ϕ=1.22 m	C6/C7	0.31, 1.62	Capacity, HETP, ΔP/H
RSR #2	Distillation	FRI, ϕ=1.22 m	C6/C7	1.62	Capacity, HETP, ΔP/H
RSR #2	Distillation	FRI, ϕ=1.22 m	iso/n-butane	6.89, 11.4, 20.7, 27.6	Capacity, HETP, ΔP/H
RSR #0.7	Distillation	FRI, ϕ=1.22 m	C6/C7	0.31, 1.62	Capacity, HETP, ΔP/H
RSR #0.3	Distillation	FRI, ϕ=1.22 m	C6/C7	0.31, 1.62	Capacity, HETP, ΔP/H
RSR #0.3	Distillation	FRI, ϕ=1.22 m	iso/n-butane	6.89, 11.4	Capacity, HETP, ΔP/H
*RSP-250	Hydraulic	SRP, ϕ=0.43 m	CO2-Air/NaOH	1.0 for ΔP/H & CO_2-Abs	ΔP/H, a_e/a_p
*RSR #0.5	Hydraulic	BUL, ϕ=0.47 m	CO2-Air/NaOH	1.0 for ΔP/H & CO_2-Abs	ΔP/H, a_e/a_p
*RSR #0.7	Hydraulic	BUL, ϕ=0.47 m	CO2-Air/NaOH	1.0 for ΔP/H & CO_2-Abs	ΔP/H, a_e/a_p
*RSR #2	Hydraulic	BUL, ϕ=0.47 m	CO2-Air/NaOH	1.0 for ΔP/H & CO_2-Abs	ΔP/H, a_e/a_p

- * Air-Water hydraulic tests conducted in 0.288 m ID column at Ruhr University Bochum for **ΔP/H** [2].
- SRP is The Separations Research Program, University of Texas at Austin.
- FRI is Fractionation Research Incorporated, Stillwater OK
- BUL is the Institute of Chemical Engineering, Bulgarian Academy of Sciences[3]

The Raschig Super-Ring (RSR) geometry is a new departure from rings, saddles or hybrids and is known as the first Fourth-Generation random packing[2]. RSR elements contain an open uniform material distribution of sinusoidal waves and multiple contact points to encourage turbulent liquid film flows over the element and minimizes drop formation.

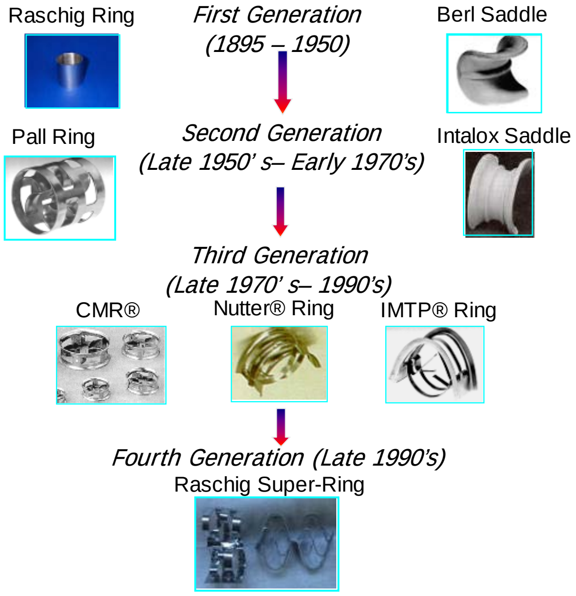

Figure 1. Four Generations of Random Packings

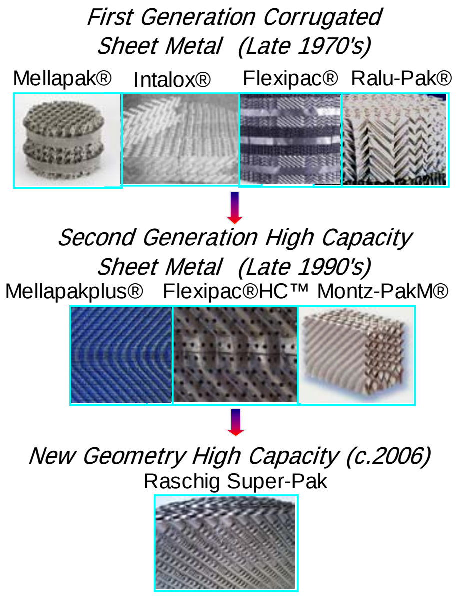

Figure 2. Generations of Corrugated Sheet Metal Structured Packings.

2.1 Efficient Capacity and No. of Theoretical Stages Comparisons – Random Packings

Figure 3 compares the maximum efficient capacities of three Raschig Super-Rings against standard and high capacity random packings. Maximum efficient capacity is defined as the last point on the HETP curve where preloading efficiency is still achieved or the last point prior to a sharp break in the HETP curve. Results for RSR® No.2, RSR® No.0.7 and RSR® No. 0.3 tested at FRI display markedly greater maximum efficient capacity and higher No. of Theoretical Stages per metre (Figure 4) than equivalent 50 and 25mm Pall Ring® sizes, and the 3rd generation series of Nutter Ring® No.2, IMTP®#40 and CMR®#2 [4,2,5].

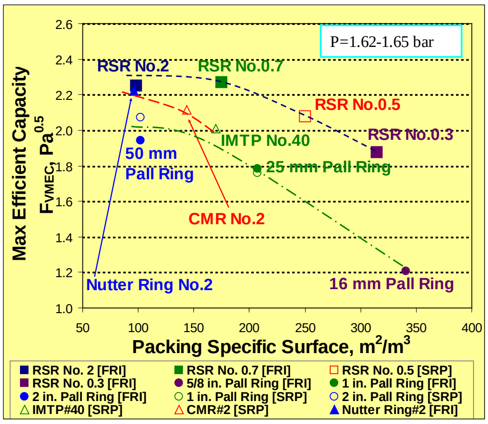

Figure 3. Maximum Efficient Capacity for Standard and High Performance Random Packings. Data from FRI and SRP Distillation Test Campaigns. Closed symbols are data from FRI 1.22m Column Open Symbols are data from SRP 0.430 m Column

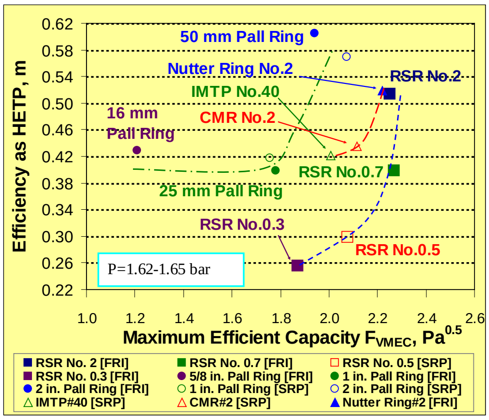

Figure 4. Mass Transfer Efficiency (NTSM) for Standard and High Performance Random Packings. Data from FRI 1.22m Test Column (closed symbols) and SRP 0.430 m Column (open symbols)

From hydraulic testing, the pressure drops (ΔP/H) of RSR® No. 2 and No. 0.7 are at least 60% lower than the Pall Ring equivalents as shown in Figure 5. Figure 6 compares the effective packing surface areas, a_e/a_p, from CO_2-air/NaOH Absorption studies (Kolev et al., 2006). The a_e/a_p parameter is the ratio of effective area for mass transfer to the packing physical specific area. For random packings, a_e/a_p exceeds unity at sufficiently high liquid superficial velocity. At these conditions the voidage space is populated with ligaments/droplets that contribute to the effective mass transfer area. Results show that the a_e/a_p of RSR® No.2 and No. 0.7 are noticeably higher than the Pall Rings. The Super-Rings uniform wave structure enhances surface area availability for homogeneous turbulent liquid film flows on the narrow lamella strips. Film flows are constantly inter-mixed on the numerous contact points within the packing element. With Pall Rings, although the production of drops contributes to the effective surface area, it is off-set by a reduction in wetting and hence mass transfer area on the ring shape.

3. Development Structured Packings

Since the 1960's structured packings have been used in various chemical process industries, from deep vacuum (rectification) up to high pressure (absorption) because of their favourable high capacity/low pressure drop/high efficiency characteristics. It began with Sulzer BX Wire Gauze, followed in the 1970's by Mellapak sheet metal with triangular corrugated channels or variations thereof as shown in Figure 2. The fluid mechanical behaviour can be summarized as follows.

Both standard and high capacity structured packings consist of triangular corrugated channels arranged in parallel planes. With each parallel plane corrugated structure placed side-by-side with opposing 45° inclinations and the size of the triangular channels determining the void space and packing surface area, the gas-liquid traffic is ultimately forced on preferred 'closed' flow paths. Additionally the two-phase flow is forced into sharp directional changes at the packing layer interface when elements are stacked at alternating 90° orientations.

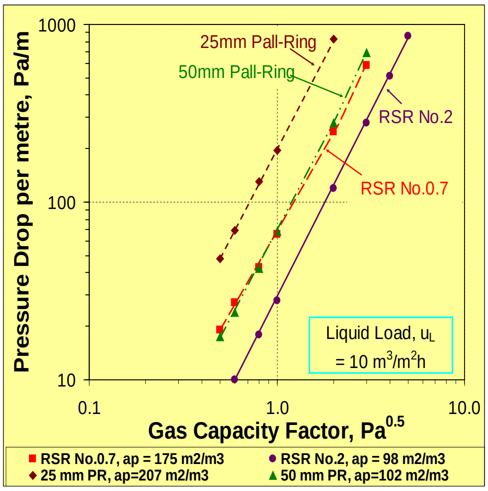

Figure 5. Pressure drop comparison of Raschig Super-Rings with Pall Ring Equivalents. Column ID 0.288m, Bed Height 1.41m. Air-water tests, Bochum, Germany.

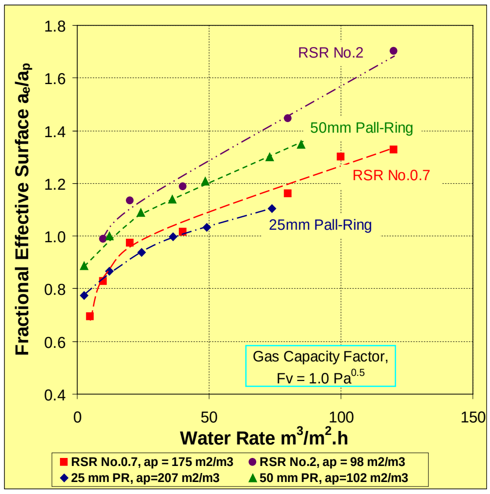

Figure 6. Fractional Effective Packing Surface a_e/a_p Comparison of Raschig Super-Rings with Pall-Ring Equivalents. Column ID 0.47m, Bed Height 2.4m

Despite vendors utilizing various surface textures (e.g. deep and shallow embossed, perforated, fluted) to enhance liquid film spreading, the fluid flow does not necessarily utilize all of the surface area (front and back of the sheets) available for mass transfer. Effective surface area is important for CO2-Capture Absorber design. Further sharp gas-liquid flow directional change and gas-gas interaction emerging from the crossing channels at the packing layer interface impose restrictive forces that affect both capacity and pressure drop.

To overcome premature flooding at the load point, standard structured packings were superseded by newer generations of high capacity structured packings such as “Mellapakplus®”, “Montz-PakM®” and “Flexipac®HC™”. These packings are characterised by bending one or both ends of the corrugated channels from 45^o to 0^o on the vertical axis at the packing layer interface, thus reducing resistance drag on the gas flow and facilitating free liquid drainage to the packing layer below. The net result is a lower pressure drop and increased capacity compared to standard types.

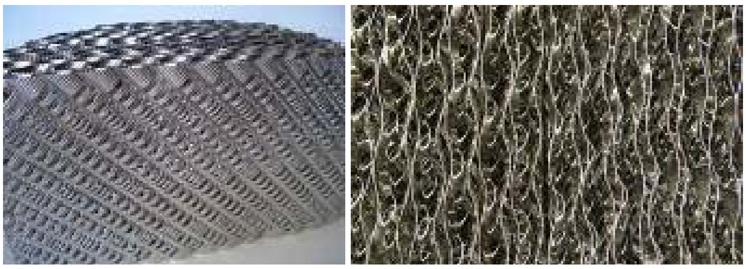

Figure 7. The Raschig Super-Pak with (a) novel regular looped structure (top) and (b) view of a packing layer in the flow direction of the gas phase (bottom)

As a result of fluid dynamic investigations the new third generation structured packing, named Raschig Super-Pak (RSP), provides remarkable hydraulic-efficiency advantages. The structural geometry consists of a regular sequence of waves above and below the plain of the metal sheet at 45^o angle of orientation. Adjacent sheets are assembled side-by-side with opposing inclinations of waves to form a layer as shown in Figure 7. RSP sheets are surface treated for greater spread of thin liquid film flows on the front and back of the wave lamellas, thus maximizing available surface area for mass transfer. The following sections will show the RSP geometry exhibiting very high capacities, low pressure drops and excellent efficiency: all advantageous for the CO_2-Capture Absorber design.

3.1 Efficient Capacity and No. of Theoretical Stages Comparisons – Structured Packings

Figure 8 compares the maximum efficient capacities of three Raschig Super-Paks against standard and high capacity structured packings. Maximum efficient capacity was defined above. Hydraulic-efficiency performance of the RSP-250 and -350 series tested at SRP are compared against the Montz B1-250, B1-350 (standard) and B1-250M, B1-350M (high capacity) structured packings tested under identical conditions[6]. The Montz packing tests were conducted at 1.03 bar in lieu of 1.65 bar. Additionally the RSP-200 is compared against standard equivalent 200 m^2m^{-3} styles structured packings[7,8]. The RSP-250 performance from FRI tests is compared with the standard M250Y and High-Capacity M252Y under identical test conditions[9].

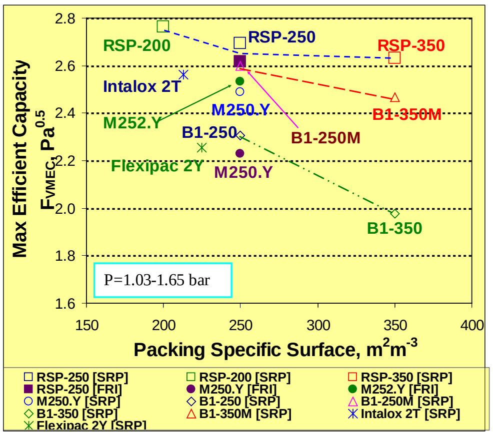

Figure 8. Maximum Efficient Capacity for Standard and High Performance Structured Packings. Closed symbols are data from FRI 1.22 m Column. Open Symbols data from SRP 0.430 m Column

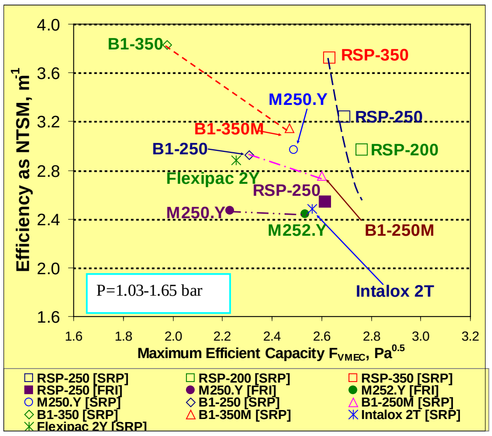

Figure 9. Mass Transfer Efficiency (NTSM) for Standard and High Performance Structured Packings. Data from FRI 1.22m Test Column (closed symbols) and SRP 0.430 m Column (open symbols)

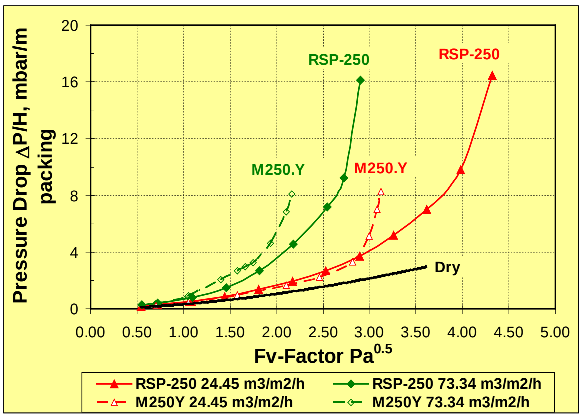

Figure 10. Pressure drop comparison of Raschig Super-Pak 250 with standard Mellapak 250.Y, Column ID 0.43 m Bed Height 3.0 m. SRP Air-Water Tests.
Solid Lines – RSP-250; Dashed Lines – M250.Y.

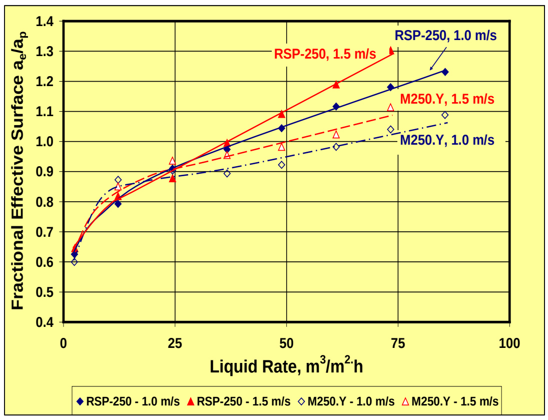

Figure 11. Fractional Effective Packing Surface Comparison of Raschig Super-Pak 250 with Standard M250.Y, Column ID 0.43 m Bed Height

Results for RSP-200, tested at SRP indicate higher maximum efficient capacities and a greater No. of Theoretical Stages per metre (Figure 9) than the standard 200 m^2m^{-3} structured packings. In Figure 8, the SRP tested RSP-250 has higher maximum efficient capacities over the standard B1-250 and high capacity B1-250M with better stage efficiencies (Figure 9). Similar trends are found with the RSP-350 versus the standard B1-350 and high capacity B1-350M with maximum efficient capacity advantages. From FRI tests, Figure 8 shows higher maximum efficient capacities for RSP-250 over the standard M250.Y and High-Capacity M252Y increased higher stage efficiencies (Figure 9).

From hydraulic testing, the RSP-250 pressure drops (ΔP/H) measured at two constant liquid loads are consistently less than the standard M250.Y as shown in Figure 10. The effective packing surface areas, a_e/a_p, are compared in Figure 11 from the SRP CO_2-Air/NaOH Absorption tests[10]. Results show that as liquid rate is increased from 24.5 to 73.3 $m^3m^{-2}h$, the effective surface of RSP-250 are higher than the standard M250.Y. At the highest rates the specific effective surface area, exceeds a value of 1 which results in a high mass transfer coefficient. With the Mellapak 250.Y, the 'closed' nature of angular channels reduces the surface area effects witnessed with the RSP-250.

Concluding Remarks

Numerous distillation, hydraulic and CO_2-Absorption test campaigns provided a sound basis for determining which packings are most suitable in Absorption/Stripping pilot plants and ultimately demonstration units where the Power Station flue gas will be utilized. Results show that Raschig Super-Pak structured packings exhibit the highest effective surface areas and lowest pressure drops which is ideal for the Absorber. With the Regenerator both Raschig Super-Rings and Raschig Super-Pak are most suitable owing to their high liquid and gas loading capacites For both packings the high effective surface area combined with high loading factors and low pressure drop lead to a reduction in column diameter and/or packing heights, less energy consumption and thus lower operating costs.

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Nomenclature

a_e	m^2	effective surface area
a_p	m^2	physical surface area
C_6	-	Cyclohexane
C_7	-	n-Heptane
ΔP	mbar/m or Pa/m	Pressure Drop
F_V	$\sqrt{Pa}$ or $m/s(kg/m^3)^{1/2}$	Gas or vapour capacity factor = $u_V \cdot \sqrt{\rho_V}$
H	m	Packing height
MEC	ms^{-1}	Maximum efficient capacity
NTSM	m^{-1}	Number of theoretical stages per meter