Distillation Absorption 2010
A.B. de Haan, H. Kooijman and A. Górak (Editors)

OPTIMIZED ABSORBER DESIGN FOR POST-COMBUSTION CCS

Markus Duss[1] and Abhilash Menon[2]
Sulzer Chemtech AG, Sulzer-Allee 48, 8404 Winterthur, Switzerland
[1]markus.duss@sulzer.com ; [2]abhilash.menon@sulzer.com

Abstract
Challenges when capturing CO_2 in post combustion applications using absorption technology are the sheer size of the columns and column internals, the pressure drop requirements to save operating costs, and the overall cost of the packing and internals. This paper addresses these challenges and it can be concluded that structured packing offers the best solution. Based on this outcome, Sulzer has developed a new Mellapak structured packing to reduces CAPEX and OPEX for such applications.

Keywords: CO_2 post combustion capture, absorption, structured packing, pressure drop, efficiency

1. Introduction

CO_2 capture from flue gases is one of the promising technologies to mitigate global climate change. Post-combustion, pre-combustion and Oxyfuel are the main competing technologies. Different technologies for post-combustion capture are under development, such as absorption (using chemical solvents), adsorption, membranes or cryogenic (anti-sublimation) processes. Using chemical solvents to absorb CO_2 can be seen as the most mature process; it has been tested in pilot plants and industrial applications. Proposed chemical solvents that have successfully passed the pilot phase include mainly amines or amino acids, and ammonia carbonate (chilled ammonia). Other technologies based on potassium carbonate, hyperbranched polymers or ionic liquids are still under investigation. Common to all processes using solvents is the need for an absorption column to provide the required interfacial area for mass transfer to allow chemical reactions with CO_2.

Main targets for CO_2 capture are coal based power stations which emit more CO_2 per kW_{el} than natural gas based power stations. Further more, the concentration in the flue gas is relatively high, typically in the range of 12 to 14 Vol-%, whereas flue gases from gas power station (CCGT) contain typically some 4 to 5 Vol-% CO_2.

2. Size is a Challenge

An average sized power station releases large volumes of flue gas to the atmosphere. Since coal based power stations are main emitters of CO_2, the example below is restricted to such a conventional coal based power station. Assuming an electricity output of 400 MW_{el} and a typical CO_2 emission of approx. 1 t / MWh_{el} (power station with 35% efficiency), the following values can be assumed:

Flue gas volume:	1'500'000 m^3/h
CO_2 emissions:	3.2 Mt/y

Absorbers to handle these high gas flow rates need to be designed accordingly. Due to the mechanism of mass transfer with chemical reaction, it is not favourable to design such absorbers at its hydraulic limit. Preferably, the columns are designed with an increased column diameter, which also allows reduction of the required packing height and the associated pressure drop. The required cross sectional area to handle a gas flow rate of $1.5x10^6$ m^3/h does not depend strongly on the solvent used. Therefore, an indicative value can be given for the required cross sectional area: assuming a gas velocity of 2.1 m/s, the required cross sectional area is 200 m^2.

2.1 Absorber Design: Round vs. Rectangular

Absorbers can be built with rectangular or round shape. It is up to the Process Licensor or Engineering Contractor (EC) to weigh the pros and cons of the chosen geometry. Materials of construction, required throughput per unit, choice of beam support options, wind loads etc. might lead to a different result concerning the cost optimized column shape. Assuming a single train to handle the flue gas rate of $1.5x10^6$ m^3/h would lead to following dimensions:

round:	diameter	16 m
square:	length	14 m x 14 m
rectangular:	length x width	20 m x 10 m

Absorber units with such dimensions are not very far from the limits of experience for column internals. When the dimensions increase further, the challenge to properly distribute the phases increases. In particular, vapour distribution needs special attention for even larger column dimensions.

2.2 Packing Efficiency and Maximum Height

The column diameter itself will not have any impact on the packing performance when appropriate initial liquid and gas distribution is assured: wall effects will be negligible. When using a structured packing such as Mellapak made of stainless steel, the maximum packing height is not restricted by the mechanical strength of the packing. Limitations might be given due to formation of maldistribution. However, absorption applications are not seen as sensitive to maldistribution since the required number of transfer units (or number of theoretical stages) to reduce the CO_2 concentration in the flue gas by 90% is low. Furthermore, the inlet concentrations of vapour and liquid are independent of the outlet concentration (unlike distillation applications). Applying a maldistribution sensitivity analysis[1],[2] confirmed the relatively low sensitivity to maldistribution.

Nevertheless, due to the very high energy demand required in the regeneration column, a good vapour and liquid distribution is key to achieve the required CO_2 loading with minimized recirculation flow rate. Sometimes, it is argued that structured packing does not perform optimal with high liquid loads but this does not hold in general and particularly not for the given conditions. The liquid load is typically in the range of 20 to 40 m^3/m^2h, the physical properties are not critical and the operating point is below or close to the loading point. Formation of inherent maldistribution by the packing itself (maldistribution independent of initial distribution) can be considered to be small. This can be qualitatively assessed by a maldistribution susceptibility analysis, which is based on the hydraulic behaviour of the system[3].

2.3 Liquid Distribution

Gravity type liquid distributors offer the required distribution quality. Spray nozzles are not recommended since they show a poor distribution quality and the high liquid entrainment is not favourable. Gravity distributors can be designed for round or square shape columns: the required distribution quality can be achieved for both column types. So-called line distributors with splash plates guide the liquid along a line to the top of the packing. A commercially well tested type is the Sulzer VEP line distributor (fig.1). The size of CCS absorbers requires an adequate pre-distribution (fig. 2, green pipes) of the solvent to the main troughs (white channels) which feed the arm channels to distribute the liquid via the splash plates accurately onto the packing. In terms of installation, VEP type liquid distributors allow a high flexibility.

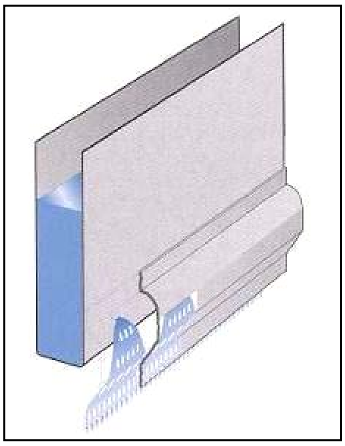

Fig. 1: Sulzer VEP distributor

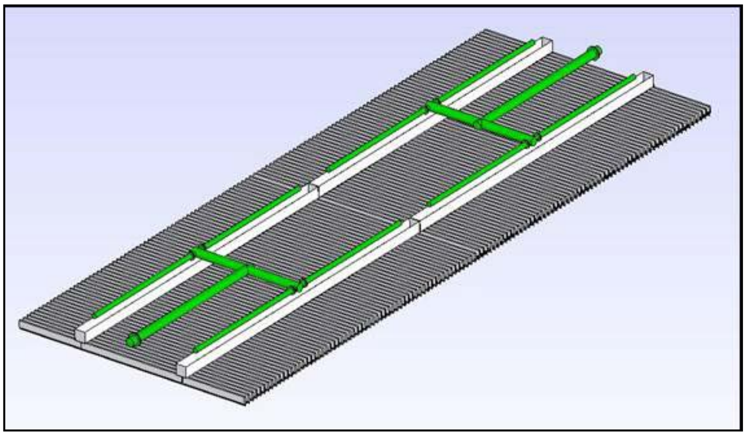

Fig. 2: Piping arrangement and liquid distributor design for a square shaped column.

2.4 Vapour Distribution

Vapour distribution is very important for large column diameters and therefore, CFD studies are required to verify the appropriate dimensioning and location of gas inlet nozzles and the required distance to the packing. Figure 3 shows a typical outcome of a CFD study. Since they increase the overall pressure drop and overall installed costs, it is favourable to avoid additional internals for vapour distribution (such as vane type gas inlets or gas distribution trays). Expertise is required to carry out and interpret the results of a CFD study.

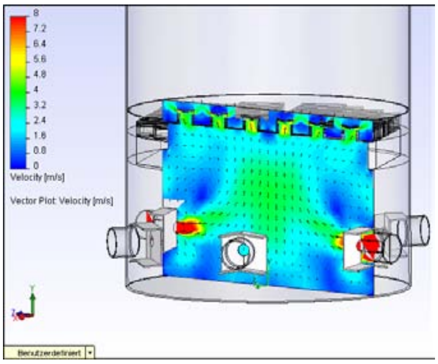

Fig. 3: CFD analysis of gas inlet

3. Minimization of Pressure Drop is Key

A gas compressor is required to compensate the pressure drop of all equipment and piping to release the treated flue gas to the atmosphere. Minimized electrical power demand of the compressor can result in substantial savings in operating costs. In order to quantify the potential saving by reducing pressure drop, a cost analysis was carried out. The life-cycle cost analysis below presents OPEX savings potential, based on electrical costs. The reduction in the pressure drop across the packing and column internals is a key parameter for saving energy. Each mbar of pressure drop saved results in considerable savings in operating cost. An example is given, calculating the annual electrical cost to overcome 1 mbar of pressure drop and assuming a vapour flow rate of 1 million m^3/h of flue gas.

Table 2: Electricity costs per mbar of pressure drop, year and 10^6 m3/h flue gas

Process Parameter	Value
Flue gas rate, G	1'000'000 m^3/h
Pressure drop reduction, Δp	1 mbar
Fan efficiency, η	0.75
Operating time, t	8'100 hr/yr
Electrical cost[1)], c	0.05 EUR / kWh
Energy per year, $E = G \times \Delta p \times t / \eta$	$3.0.10^5$ kWh / year / mbar
Electrical costs, $C = E \times c$	EUR 15'000 / year / mbar

1) Average electrical cost in EU25 countries (Eurostat, 2007)[4]

Power plants are designed for a life- span of up to 30 years. Therefore, longer pay back times can be accepted than commonly required for investments in the chemical and petrochemical industry. The net present value method (NPV) allows to asses the pay back time to judge the investment. The cumulated NPV is shown in figure 4 and should be interpreted as follows: if investment costs of €75'000.- or €100'000.- or €125'000.- are executed to reduce 1 mbar of pressure drop with 1 million m3/h of flue gas, then the pay back time is 7, 10 or 15 years, respectively, assuming a WACC of 8.5%.

Example: a packing which reduces the pressure drop by 5 mbar with a gas flow rate of 1.5×10^6 m^3/h, is worth higher investment costs of up to 750'000 EUR (assuming a required pay back time of 10 years). Evaluation of such costs needs to be considered during the absorber design and when choosing the type of packing and associated internals.

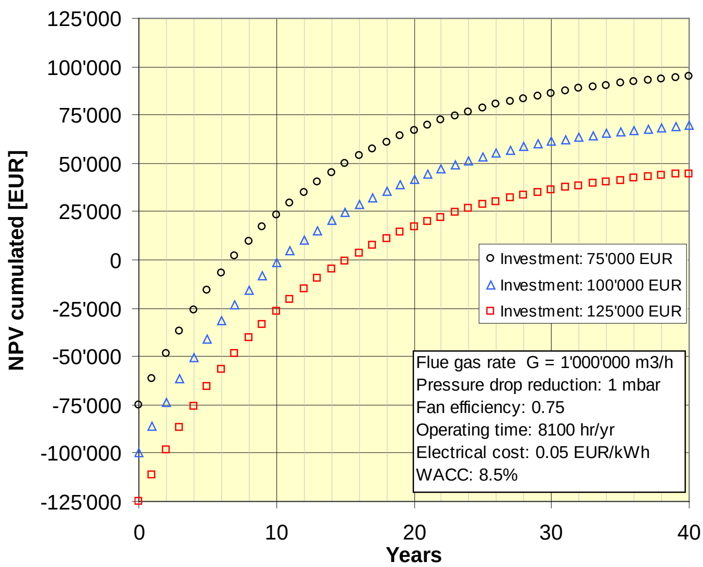

Figure 4. Cumulated net present value vs. operating time.

4. Cost of Internals

Column internals for absorbers and strippers contribute significantly to the overall investment costs for the capture unit. Related to column internals, the material cost is by far the biggest contributor. Hence, optimising the cost of internals requires minimizing the amount of material used for the packing manufacturing. Due to the geometry of Sulzer Mellapak or similar structured packing types, the mechanical strength is significantly improved compared to any random packing and allows manufacturing from very thin sheets. Therefore the amount of material required for structured packing is significantly less than for random packing: out of one kg of stainless steel, more than double the geometrical surface area can be formed of structured packing compared to random packings. A ring with the same specific area requires typically 2 to 3 times this amount of material. The lower material demand for stainless steel structured packing more than compensates the increased production costs, especially for the very high volumes considered here. Concerning operating costs, Mellapak shows optimal behaviour due to the low pressure drop. The value of low pressure drop is significant as presented in section 2. Costs for installation of structured packing are higher compared to rings, however, the overall contribution of manufacturing and installation costs are relatively low and do not change the conclusion: Sulzer Mellapak structured packings show optimal behaviour for CO_2 absorbers.

5. Mass Transfer with Chemical Reaction

For an optimized absorber design, the mechanism of mass transfer needs to be understood. The absorption of CO_2 with chemical solvents consists of the following steps (fig. 5):

- mass transfer of CO_2 in the vapour phase through the film to the interfacial area
- mass transfer across the interface (however, no resistance to mass transfer assumed)
- mass transfer of the physically dissolved CO_2 in the liquid phase from the interface into the bulk of the liquid phase
- reaction of the CO_2 with the solvent (e.g. amine) in film and bulk of the liquid phase

Figure 5 shows the principal mechanism of the behaviour of CO_2 based on the two film theory of Whitman[5]. Resistance to mass transfer is assumed to be solely within the laminar films of each phase: CO_2 is transported by molecular diffusion within these laminar films and the thickness of the film is a packing characteristic which defines the liquid and vapour mass transfer coefficients, k_L and k_G, respectively. There is no concentration gradient in the bulk of each phase due to convection. The physical mass transfer of systems for components with low solubility (CO_2) tends to be liquid side controlled. This can be easily derived from the overall mass transfer coefficient K_{OG}, which includes vapour and liquid side resistances[6]:

$$\frac{1}{K_{OG}} = \frac{1}{k_G} + \frac{m}{k_L} = \frac{1}{k_G} + \frac{H/p}{k_L}$$

m is the slope of equilibrium line and the Henry coefficient, H, divided by the operating pressure, p, can be used instead. Since the Henry constant for CO_2 in aqueous system is in the order of magnitude of 1000 bar, the overall mass transfer coefficient is determined by k_L and *H / p* whereas k_G is negligible i.e. the system is liquid side controlled.

Generally, the resistance to mass transfer depends on packing characteristics (i.e. the thickness of the laminar film of vapour and liquid phase), on the operating conditions and on the physical properties of the fluids. Depending on the reaction kinetics of the chemical solvent used, the reaction of CO_2 with the base component can be fast enough so all of the CO_2 is reacted within the laminar liquid

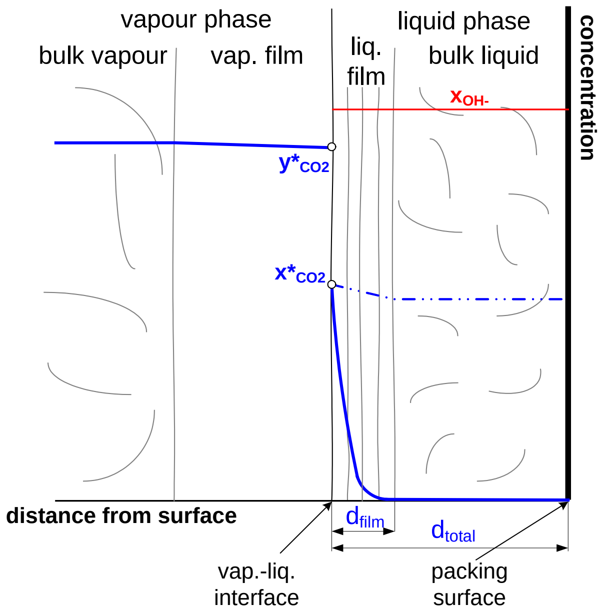

Figure 5. Two-film model acc. to Whitman CO_2 concentration profile with and without reaction.

film i.e. no un-reacted CO_2 remains in the bulk of the liquid phase as represented by figure 5. Any system which can be categorized as such belongs by definition to the ***'fast reaction regime'***. The example shown holds for CO_2 and OH^-, assuming an irreversible reaction where the CO_2 equilibrium concentration is zero. However, also for reversible reactions the conclusion is valid. For these reactions, the CO_2 concentration in the bulk of the liquid is in chemical equilibrium. A typical test system for a fast reaction regime is CO_2-NaOH and is discussed in detail in literature [7]. Also many systems with significantly lower reaction kinetics are still categorized as fast reacting, e.g. MEA and many other amines and amino acids as used in post-combustion CO_2 capture units might be categorized in the fast reaction regime. The outcome of the interpretation of the fast reaction regime is, that the interfacial area is the main property which determines the mass transfer rate for a given kinetic reaction. In section 3, it was shown that a main advantage of Mellapak over random packing is the high geometrical area offered Therefore, a packing geometry like the Mellapak structured packing offers the best basis to further optimize the packing geometry specifically for post-combustion CO_2 capture applications.

6. An Optimized Solution

A Mellapak structured packing is a good solution for post-combustion CO_2 capture absorbers due to the low amount of material required per unit geometrical area and due to the low pressure drop. To further improve the geometry of Mellapak structured packing specifically for post combustion capture applications, the following optimisation strategy was chosen: the properties of Mellapak structured packing shall be modified to maximize the effective interfacial area (or wetting) while minimising the pressure drop at the same time. Mellapak types with a relatively low specific area between 200 to 250 m^2/m^3 show a better wetting behaviour than packing types with large geometrical area (because of the increased liquid flow rate per perimeter). Due to the low pressure drop, the X-type is preferably used in this specific application and M2X can be seen as the benchmark. 'X' indicates a corrugation angle 30° in respect to the vertical; 'Y' indicates 45°. The target for an improved Mellapak geometry was therefore to have at least the same efficiency as M2X but a lower pressure drop for typical operating conditions as expected in post combustion applications. Modifications to the Mellapak geometry were systematically screened to achieve the targeted improvements. The influence of micro structure, hole size, numbers of holes, angle of corrugation and influence of the ratio of layer height to base length need to be understood to find an optimized solution. Modifications to the Mellapak geometry were found to satisfy the targeted improvements and 2 new modifications were finally developed and tested. Figures 6 and 7 show measured data for 2 different versions of Mellapak (Type-1 and Type-2) and the data are compared to M2X. To compare the hydraulic behaviour, an air-water system was used and CO_2-NaOH was used to measure the efficiency, i.e. the effective interfacial area of the various packings. Air (containing some 380 ppm-Vol of CO_2) was used to measure the absorption rate of CO_2. The effective interfacial area was evaluated using published open literature[8].

The two versions of Mellapak evaluated finally were: Mellapak Type-1 with the objective to minimize production costs of the packing while reducing pressure drop and maintaining efficiency compared to M2X and Mellapak Type-2 with the objective to minimize overall costs (CAPEX and OPEX). As shown in figure 6, the pressure drop could be reduced by 20% compared to M2X with Mellapak-1 and Mellpak-2 whereas the efficiency could be maintained on the level of M2X for the first type (figure 7) and Mellpak-2 even shows up to 20% improved efficiency. However, the costs to manufacture Mellapak Type-2 is increased compared to Mellapak Type-1. The features of the modified Mellapak offer cost optimized solutions for post combustion CO_2 capture applications. It is shown that reducing the corrugation angle in respect to the vertical from 30° to 25° resulted as expected in 10% to 15% lower pressure drop compared to standard M2X (fig.6); however, the effective interfacial area was considerably reduced at the same time (figure 7). Furthermore it should be noted that the operating range where the new Mellapak types achieve the claimed advantages is limited to operating conditions as typically found in post combustion absorbers, i.e. when the operating point is close or below the loading point and when the systems can be categorized as fast reaction regime. For vapour side controlled systems (e.g. distillation) the new geometry does not result in such improvements.

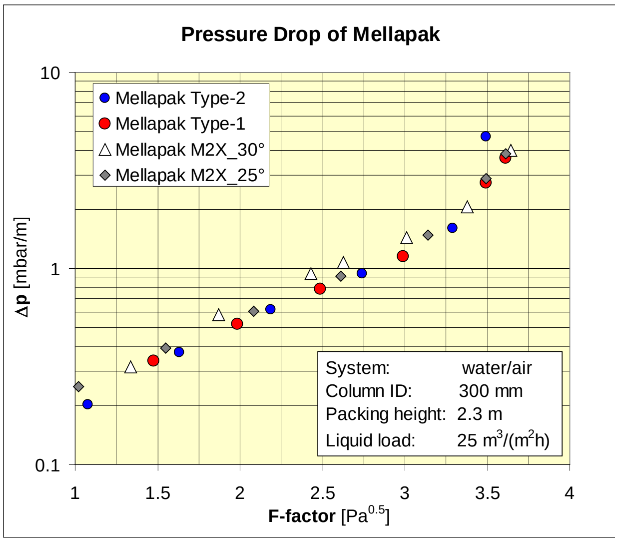

Fig. 6: Pressure drop of new Mellapak Type-1 and Type-2 compared to M2X

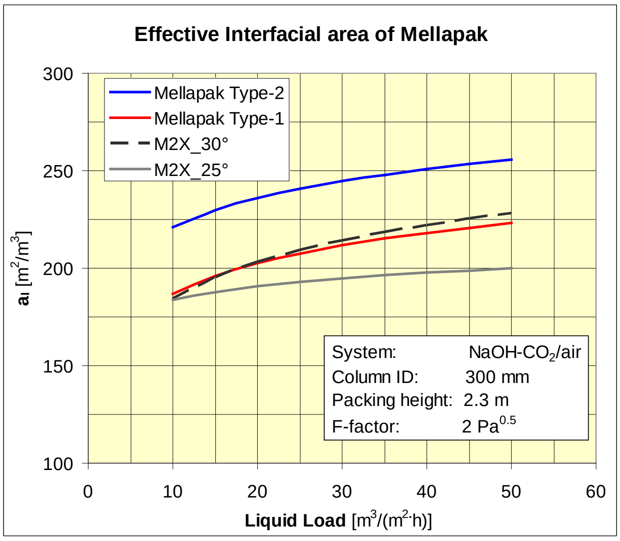

Fig. 7: Efficiency of new Mellapak Type-1 and Type-2 compared to M2X

The results in figure 7 were obtained by absorbing CO_2 from air (i.e. 380 ppm.-Vol CO_2) using a 1 molar sodium hydroxide solution. Due to the low CO_2 concentration in air, the caustic strength changes only very slowly with time and remains therefore virtually constant. However, the caustic and carbonate concentrations itself as well as the temperature, have a significant impact on the results and need to be accurately measured when evaluating the interfacial area.

The test system CO_2-NaOH is irreversible and therefore the bottom liquid can be recycled to the top of the absorber without regeneration. Since the driving force is virtually independent of the local L/V-ratio, liquid maldistribution has little impact on the measured efficiency because the caustic solution does not become depleted. This might not hold true for chemical solvents as used in post-combustion capture units. The driving force will be reduced in zones with reduced liquid film velocities. Therefore, attention needs to be paid, when optimising the geometry based on CO_2-NaOH. Results indicate that for corrugation angles which are significantly steeper than 30°, the risk of inherent maldistribution formation increases. The geometry of the new Mellapak accounts for this fact.

7. Conclusions

Structured packing like Sulzer Mellapak can contribute to a cost optimized solution considering investment and operating costs when building post-combustion absorbers. The minimized material requirement, the low pressure drop and the high effective interfacial area offered by Mellapak are the basis for this claim. Optimisation of the packing geometry lead to a new Mellapak modification, which offers an optimised efficiency with minimised pressure drop for liquid side controlled applications involving a fast chemical reaction. Post-combustion CO_2 absorbers are typically categorized in this regime.

References

1. H. Yuan and L. Spiegel, *Chem.-Ing.-Tech.*, 54(1982)
2. J.F. Billingham and M.J. Lockett, *Chem. Eng. Res. Des.*, 80(2002) 373-382
3. M. Duss, *Symposium Series No. 152*, 2006 IChemE, 418-430
4. Eurostat (2007), http://epp.eurostat.ec.europa.eu/
5. W.G. Whitman, *Chem. Metall. Eng.*, 29 (1923) 146-148
6. R.H. Perry and D. Green, *Perry's Chemical Engineers' Handbook*, 6th Edition, McGraw-Hill
7. T. Weimer and K. Schaber, *Chem. Tech.*, 5(1996) 241-249
8. M. Duss et.al., *Chem. Eng. Technol.*, 24(2001) 716-723