

Post-combustion capture of CO₂

Case study of a generic amine-based absorption process. A lifecycle cost analysis for a power plant over a 40-year span clearly shows the advantages of structured packing over random packing

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The past few years have seen an unprecedented interest in proving the techno-economic viability of CO₂ capture technologies from power plants flue gas streams. The main challenge is removing concentrations of CO₂ (typically 3.5–14 vol%) from large volume gas streams, which leads to very large column sizes. An important cost factor is the pressure drop per metre that can be saved inside the absorber. Structured packing offers an excellent solution in terms of both reducing the column's dimensions (Capex) and providing a low pressure drop (Opex) over the absorber. The correct choice of gas and liquid distributor devices is also critical in the success of such large-scale industrial applications.

CO₂ control initiatives

The past few years have seen significant interest worldwide in the handling of carbon dioxide (CO₂). This is primarily linked to responsible utilisation of fossil fuels. Climate change and greenhouse gases (GHG) emissions have become a daily topic of discussion as world governments, politicians, industries, NGOs and the general public contemplate how to tackle this global problem. CO₂ emissions from fossil fuel combustion are considered to be the primary contributor.

As a result, there has been considerable international interest in the development of technology for capturing and storing CO₂. The current available technology is highly expensive, and there are many uncertainties linked to the costs and operation of a CO₂ chain. For example, the cost of capturing CO₂ from a coal-fired power plant amounts to approximately two-thirds of the cost of the entire CO₂ chain, while transport and storage amount to approximately one-third (Norwegian Ministry, 2008). Capturing CO₂ requires a lot of energy. The IPCC report (Norwegian Ministry, 2008) assumes that, if 90% of the CO₂ from a power plant is captured, fuel consumption will increase by 11–40%,

depending on the technology and the fuel. The report estimates that CO₂ capture increases the production costs associated with power production by 20–85%. If the current level of research and development is maintained, the cost of capturing CO₂ could be reduced by 20–30% over the next ten years.

Technically, there is no problem in separating CO₂ at very low concentrations from flue gas streams. This is a well-established process within the gas processing, petrochemical and fertiliser industry. Gas absorption into chemical solvents such as amines is the most promising technology due to its capacity to handle large volumes of flue gas, plus it can be operated at a low temperature and pressure.

Flue gases from gas or coal-fired combustion plants typically contain some oxygen. Monoethanolamine (MEA)-based solvents with additives and corrosion inhibitors are commonly used in applications for flue gases. MEA-based processes look attractive due to their fast reaction rate with CO₂ and the low cost of raw materials compared with other amines. However, MEA absorption processes are associated with high operating costs because of the significant amount of energy required for solvent regeneration, and severe operating problems such as corrosion, solvent loss and solvent degradation.

Post-combustion CO₂ capture technology

Technology for capturing CO₂ from gas and coal-fired power plants can be divided into three main categories: post-combustion, pre-combustion and oxy-fuel. Post-combustion entails separating CO₂ from the exhaust gas of the power plant using chemical scrubbing. This technology, in principle, can be utilised in existing power plants without major modifications. Post-combustion is the most mature technology, although there is still significant uncertainty surrounding its use. The main problem is the low partial pressure of CO₂ in the

flue gas, which also contains other gases such as oxygen, water vapour and nitrogen. Separation methods are required to trap CO₂ preferentially, so it can be compressed and stored in a sequestration site, complying with regulations for CO₂ purity.

So far, none of these technologies have been subjected to large-scale testing in gas power plants. Therefore, there is much uncertainty associated with the use of the available technology for CO₂ capture, particularly with regards to costs and performance.

Techno-economic design study

As previously noted, it is important to choose the right technology for mass transfer when it comes to applications such as CO₂ capture, where pressure drop can be a significant factor in operating costs. While an industrial case study has been chosen to emphasise this point, it is not our intention to discuss process-specific parameters related to heat duty optimisation, energy/exergy analyses and so on, but rather to convey some essential concepts that must be understood and accounted for at an early stage in the design process.

Case study

Figure 1 provides a schematic overview of the amine-based scrubbing process for CO₂ capture from a flue gas stream (eg, coal-fired power plant flue gas stream). The process conditions for this case study have been taken from Alin (2007). This study is performed on a 800 MW coal-fired power station, which is reasonable for a medium-sized power plant in Europe. The various process conditions, parameters and assumptions are summarised in Table 1. Simulations presented herein are performed using the commercially available tool ProTreat from OGT (2008). ProTreat is a rate-based modelling tool that uses mass transfer correlations readily available in literature for random packing (Onda, 1967) and structured packing (Bravo &

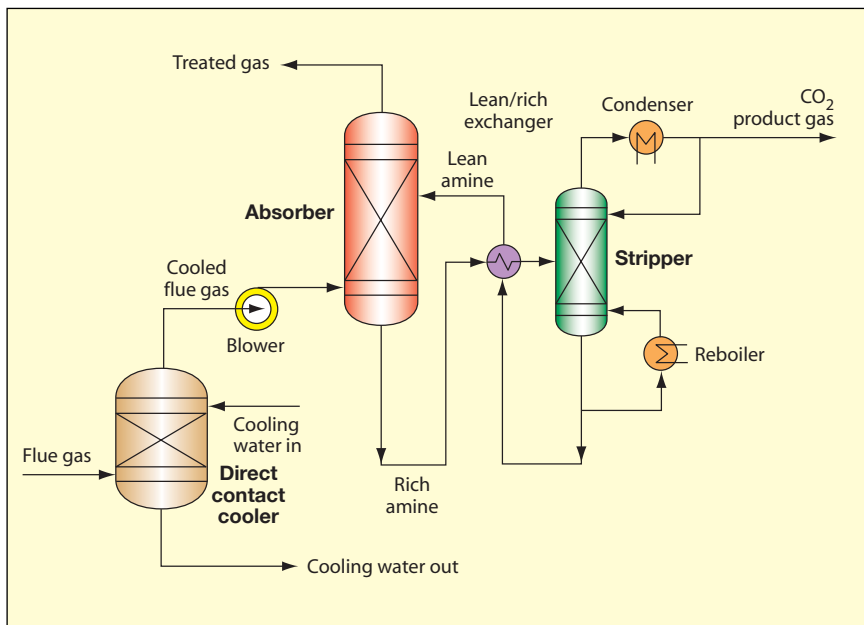


Figure 1 Schematic of CO₂ capture plant based on amine scrubbing process

Process conditions used in the ProTreat simulation model	
Process parameter	Value
Flue gas temperature and pressure at absorber inlet	46°C/1.02 bar
Flue gas composition	
CO ₂	12.4 mol%
H ₂ O	9.9 mol%
O ₂	5.0 mol%
N ₂	71.8 mol%
Ar	0.9 mol%
Flue gas flow rate at absorber inlet	3.07. 10 ⁶ kg/hr
Treated gas temperature and pressure	60°C/1.02 bar
Lean amine temperature and pressure at absorber inlet	40°C/1.03 bar
Lean amine (MEA) concentration	30 wt%
Lean amine circulation flow rate	7.20.10 ⁶ kg/hr

Table 1

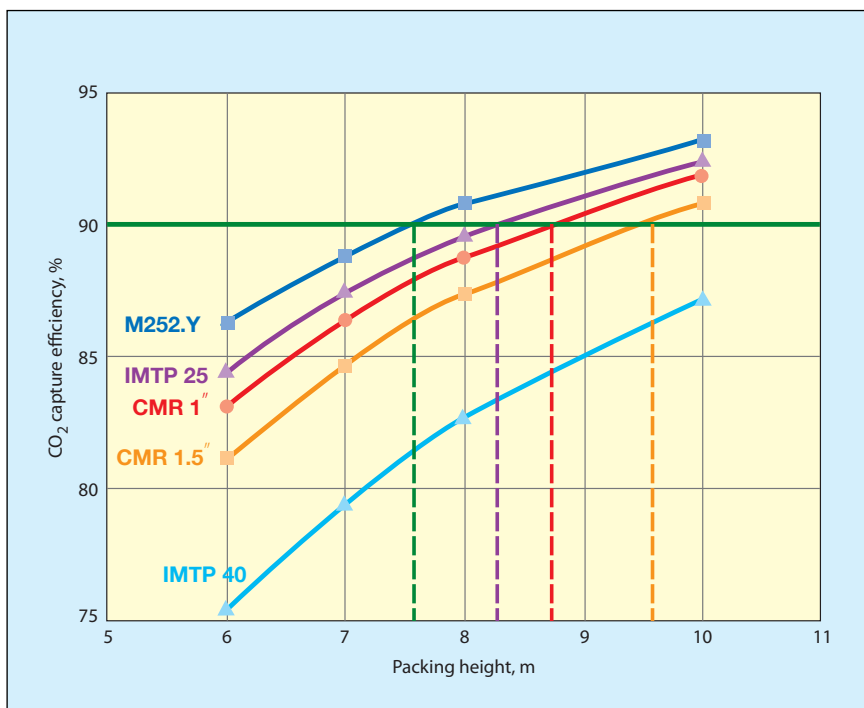


Figure 2 CO₂ removal efficiency as a function of packing heights for structured and random packings. A separation performance of 90% is the yardstick for comparison

Fair, 1992). The amine selected for this simulation is MEA, which is a widely used generic amine for sour gas treatment purposes. The simulations were run for a CO₂ loading of 0.15 mol CO₂/mol amine in the lean amine stream entering the absorber. Of course, the CO₂ loading is directly coupled with the reboiler heat duty, but that discussion is outside the scope of this article.

The absorber is operated close to atmospheric conditions, which implies that pressure drop within the absorber is a critical factor when designing the column (ie, a higher pressure drop requires higher energy input into the fan, which feeds the flue gas into the absorber). This simple philosophy virtually rules out using trays as a mass transfer device in the absorber because of the significant pressure drop losses. Therefore, choosing the right mass transfer technology within the absorber can result in huge potential savings in both capital and operating expenses. The comparisons presented are for structured and random packings available in the market.

The simulations are for a standalone absorber only, as this is the largest column in a CO₂ capture plant (CCP), so it has the biggest impact on the economics of the process. An important factor to consider here is the lifecycle of a power plant, which tends to be 30–40 years, compared to ten years for a petrochemical plant.

Mass transfer technology for CO₂ absorption

Comparison of the various mass transfer devices was based on two criteria: similar geometrical surface area for the packing and similar operating capacity of the column. The internal diameter (ID) of the absorber was fixed at 21m. This was arrived at by simulating the process with structured packing MellapakPlus M252Y, which gives a column capacity of around 68%. If a system factor is taken into account for foaming, this value should be derated. For this study, the design criteria for the column's hydraulic capacity is fixed at 70%. The chosen packing types are listed in Table 2. These mass transfer devices will be compared on the basis of their separation efficiency, hydraulic performance and, most importantly, associated costs (Capex and Opex).

As seen from Table 2, structured packing MellapakPlus M252Y and random packing CMR1" have the same geometrical surface area of 250 m²/m³, and IMTP25 is close at 226 m²/m³, which could make for some interesting comparisons. As will be seen later, CMR1.5" has a similar capacity to M252Y. IMTP40 is also included, as it has a higher capacity than IMTP25, so it will be interesting to see its separation performance.

Packing characteristics for structured and random packing used for simulations

Packing type ²	Geometrical area, m ² /m ³
M252Y	250
CMR1" ^a	250
CMR1.5" ^b	187
IMTP25 ^c	226
IMTP40 ^d	151

a Sulzer equivalent C-Ring 1"; b Sulzer equivalent C-Ring 1.5"; c Sulzer equivalent I-Ring 25; d Sulzer equivalent I-Ring 40

Table 2

Separation performance

Based on the results from simulations using ProTreat, Figure 2 shows the separation performance of M252Y compared to all the listed random packings. A packing height of around 7.6m for M252Y is enough to achieve a CO₂ separation efficiency of 90%. CMR1", with a similar geometrical area to M252Y, requires 13% more packing height, while CMR1.5", with a similar capacity to M252Y, requires 20% more than M252Y.

It is obvious from these results that structured packing offers significant advantages in terms of reducing column heights. Obviously, ProTreat simulates a higher separation efficiency for structured packing than random packing. Therefore, the packing height for a desired separation performance will be lower for structured packing, which translates directly into a further reduction in total pressure drop, as can be seen in the following section.

Hydraulic performance

Structured packings have a significantly lower pressure drop per theoretical stage than random packings when comparing packings of similar efficiency. Pressure drop considerations assume more importance for an application like CO₂ absorption from flue gas streams, which are under atmospheric conditions. Every saving in the total pressure drop over the column amounts to significant savings in operating expenses (eg, the energy required for the fan blower).

For a given CO₂ capture efficiency of 90%, Figures 2, 3a and 3b show the benefits gained by using M252Y over random packings in terms of separation efficiencies and hydraulic capacities/pressure drop. An interesting result here (see Figure 3a) is the difference in hydraulics estimated by ProTreat and Sulcol.³ For an ID of 21m, hydraulics provided by Sulcol show a capacity of around 57%, which implies that the column is over-designed (whereas ProTreat gives a value around 70%). A quick estimation in Sulcol to match the 70% capacity criteria shows that an ID of

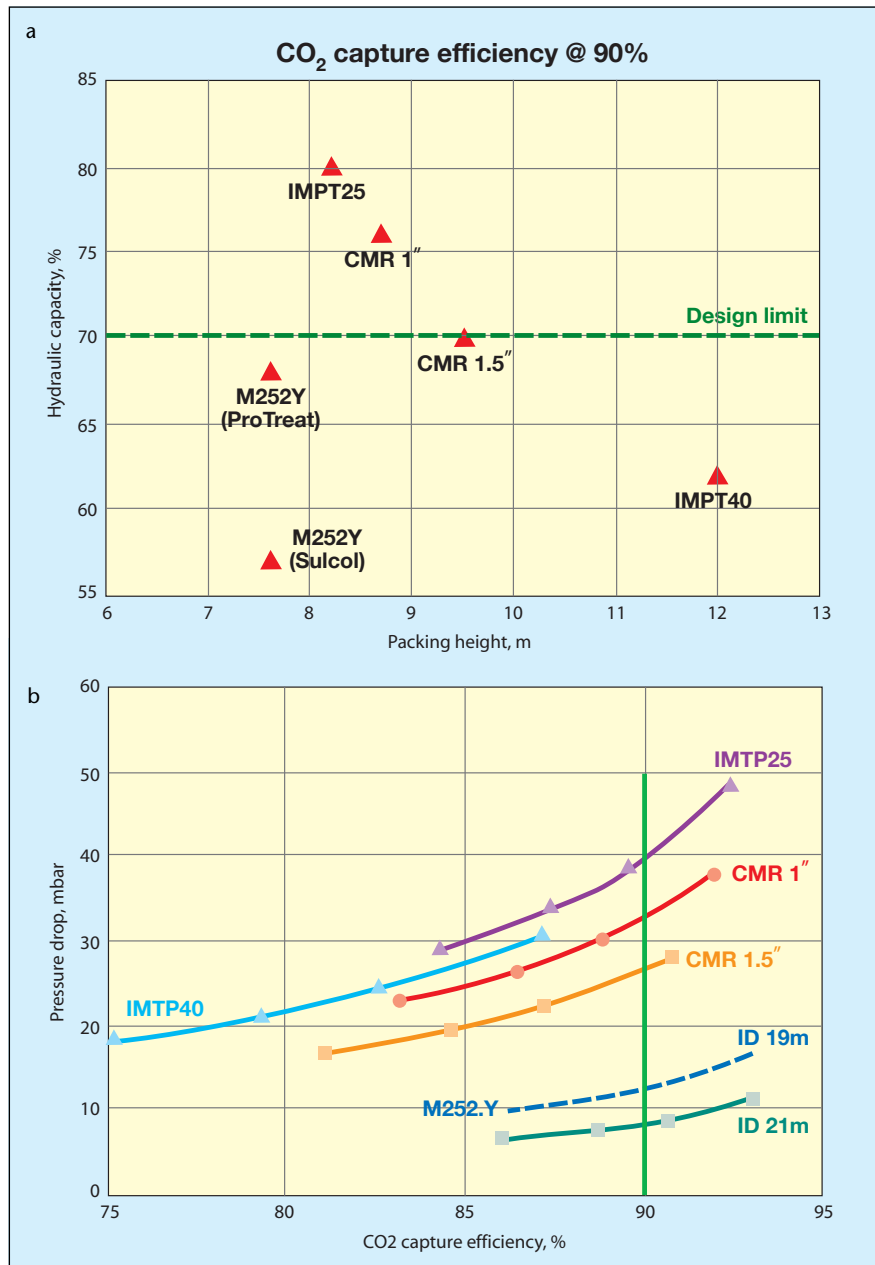


Figure 3 Hydraulic characteristics for CO₂ absorber for commercially available packings. The dotted M252Y curve in (b) reflects the hydraulics for an absorber with an ID of 19m. All remaining curves are for an absorber ID of 21m

19m is good enough to meet the hydraulic performance requirements. Of course, for this lower ID of 19m, the corresponding pressure drop goes up by around 50% with respect to an ID of 21m (see dotted curve for M252Y in Figure 3b). Actually, Figure 3b provides an interesting perspective in terms of the overall pressure drop over the packed bed height for various separation efficiencies. M252Y offers the lowest pressure drop among all the packings, with its pressure drop more than halved. It will be shown later how these savings in pressure drop (each mbar saved) can translate into significant cost savings for the end user.

Savings in capital and operating expenditures Capex savings

A higher separation efficiency for a

given performance target implies that packing bed heights can be reduced. As noted in Figure 2, M252Y can reduce column bed heights by up to 20% compared to random packings, which means the column heights could be correspondingly lowered, resulting in lower capital expenses. As also observed in Figures 3a and 3b, M252Y offers higher hydraulic capacities (or lower total pressure drop) compared to random packings. Thus, the column internal diameters can be reduced (by up to 10% in this case), which again contributes to a lower Capex.

These benefits go hand-in-hand with the total material weight (cost) of the packings. Random packings require more material for manufacture (in terms of sheet thickness) than structured packings, so depending upon the

packing type chosen, random packings can weigh up to two to three times more than structured packing.

Opex savings

Here, a lifecycle cost analysis is presented for possible Opex savings, based on electrical costs (pressure drop). A fan is required to force the large flue gas stream through the absorber. A 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. Table 3 calculates the annual electrical cost to overcome 1.0 mbar of pressure drop and assumes a vapour flow rate of 1 MM³/h of flue gas. The calculation results in €15 000 saved per each mbar and per 1.0 MM³/h of gas. The flue gas from an 800 MW coal power station or a 400 MW gas power station is close to 2–3.0 MM³/h (see Table 1).

Hence, when comparing various absorber designs, attention needs to be paid to the total resulting pressure drop. In order to judge investment costs resulting in pressure drop reduction, the net present value method (NPV) can be applied. Usually, the required investment to achieve a higher cash flow is known and the NPV method is used to judge the economic feasibility. In this case, the investment is not calculated. Instead, three values are arbitrarily chosen to evaluate the benefit of such an investment. The objective here is to quantify the investments made to reduce pressure drop in terms of the internal rate of return (IRR) and the pay-out time.

Figure 4 shows the NPV curve, assuming an interest rate of 8.5% (WACC, weighted average cost of capital) for three cases, with an invested capital of €75 000, €100 000 and €125 000,

Electricity costs for a medium-sized European power plant	
Process parameter	Value
Flue gas rate, G	1 000 000 m ³ /h
Pressure drop reduction, Dp	1 mbar
Fan efficiency, h	0.75
Operating time, t	8100 hr/yr
Electrical cost ¹ , c	0.05 EUR /kWh
Energy per year, E = G x Dp x t/h	3.0.10 ⁵ kWh/year
Electrical costs, C = E x c	EUR 15 000/year

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

Table 3

Cash flow analysis for investment made to reduce pressure drop			
Invested capital (€) per mbar per 1 MM ³ /hr	75 000	100 000	125 000
Assume life span, years	IRR, %	IRR, %	IRR, %
20	19.4	13.9	10.3
30	19.9	14.7	11.5
40	20.0	14.9	11.9
Pay-out time	7	10	15

Table 4

respectively, for a reduction of 1.0 mbar pressure drop and a flue gas rate of 1.0 MMm³/h.

Power stations typically have a lifespan of 30–40 years. The IRR indicates the achieved interest on the invested capital over that lifespan. Therefore, the IRR for a power station can be based on a time period that is much longer than the chemical and hydrocarbon processing industry is used to. Table 4 shows the IRR, assuming a lifespan of 20, 30 and 40 years, respectively.

Investments to reduce pressure drop can be as high as €125 000 for each mbar of pressure drop reduction for a flue gas rate of 1.0 MM³/hr, depending on the required IRR and assumed lifespan. The use of structured packing in the CO₂ absorber results in significant pressure drop savings compared to

random packing, so structured packing is preferred in this service. For a 800 MW coal-fired power station, a reduction of even 5.0 mbar can be worth more than €1.0 MM, with a pay-out time of seven years and an IRR of around 20%. This definitely needs to be taken into consideration during when designing the CO₂ absorber.

Not just the choice of packing must be considered, but also the overall column dimensions and the other column internals, such as liquid distributors and draw-off trays. Alternatively, columns might be built larger in diameter, which is commonly perceived as a means of minimising pressure drop.

Again, it is important to bear in mind that the overall savings will be down to the right combination of Capex and

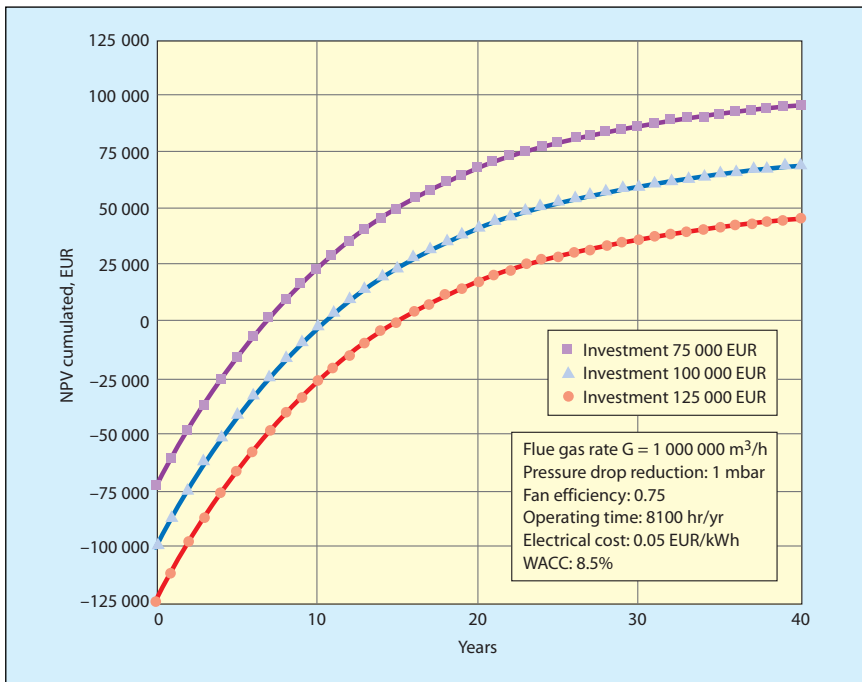


Figure 4 Net present value (NPV) curve for a period of 40 years

Opex. A smaller diameter implies a higher pressure drop and vice versa. So, essentially, this becomes a trade-off between Capex (smaller ID) and Opex (higher pressure drop) or vice versa, which the process designer should account for in the design phase.

Liquid and gas distribution for large CO₂ absorbers

Gravity-type distributors for the distribution of liquid in the absorption sections are recommended. For lower liquid loads, a line distributor can provide adequate distribution. To avoid problems with fouling, the distributors must be equipped with larger orifice sizes and openings on the side walls. To allow for adjustments in the operation of the column, a turndown range of three to one can easily be realised with gravity distributors. The open area of the distributor influences the pressure drop of the column. A typical open area of

30–40% can be realised with standard configurations (Figure 5).

For higher liquid loads (>10 m³/m²h), high load gravity distributors are used in combination with a well-designed inlet system. The inlet system is designed to allow a proper pre-distribution to the liquid distributor.

The distributors are built in segments to allow them to be installed through manway openings. The distributors have to be level during operation. On structured packing sections, the distributors can be supported by the packing itself. An integrated support system with the capability of levelling the individual parts of the distributor is placed on the packing surface. The mechanical strength of the structured packing is able to support the distributor, including its liquid load. If random packing is used, the distributor has to be suspended on beams. The distributor layout can be easily adjusted for circular

or rectangular column cross-section layouts.

Collect and redistribute

To draw off liquid from a section, the liquid has to be collected by a collecting device. Collectors have to be designed with a minimum pressure drop and, depending on requirements, should be as sealed as possible.

The required distribution quality of the vapour flow is not the same as for liquid, but is still important to allow for an even L/V ratio in the packed section. The vapour distribution is mainly influenced by column shape, the configuration of the vapour inlet pipes, inlet devices and the available pressure drop of the packed bed above the vapour inlet (Figure 6). All these parameters need to be accounted for when the vapour distribution quality is verified. CFD tools allow you to visualise and analyse the vapour distribution quality below packed sections. To allow for a definition of the vapour distribution quality, the variation of the vertical velocity is compared over the column cross-section at the packing inlet. The position of the vapour inlet nozzle in rectangular column layouts has more influence on vapour distribution quality than a circular arrangement.

Conclusions

The right selection of mass transfer technology is crucial to the successful techno-economic feasibility of CO₂ capture from post-combustion power plants. Comparing the separation efficiencies and hydraulic performance of the various packings, structured packing is clearly preferred in this application. Even a 5.0 mbar reduction in total pressure drop over the column can be worth more than an initial investment of €1.0 MM. It is possible to achieve a two to three times greater reduction in pressure drop using structured instead of random packing. On deciding whether to go for a larger diameter with a smaller pressure drop or

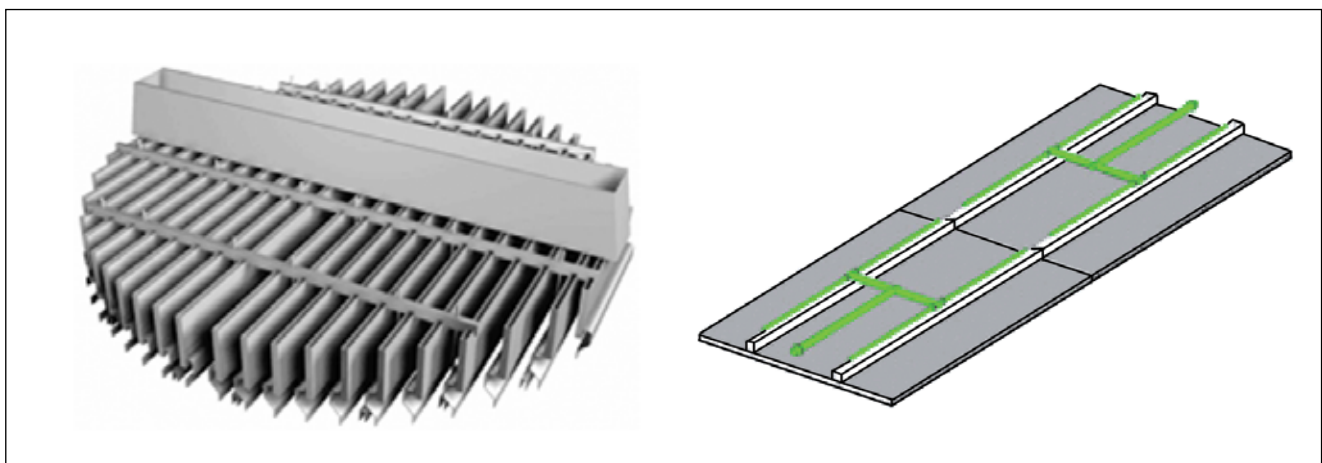


Figure 5 Sulzer liquid distributor configurations: (left) splash-plate distributor (right) rectangular layout of a high load distributor including the arrangement of the liquid inlet

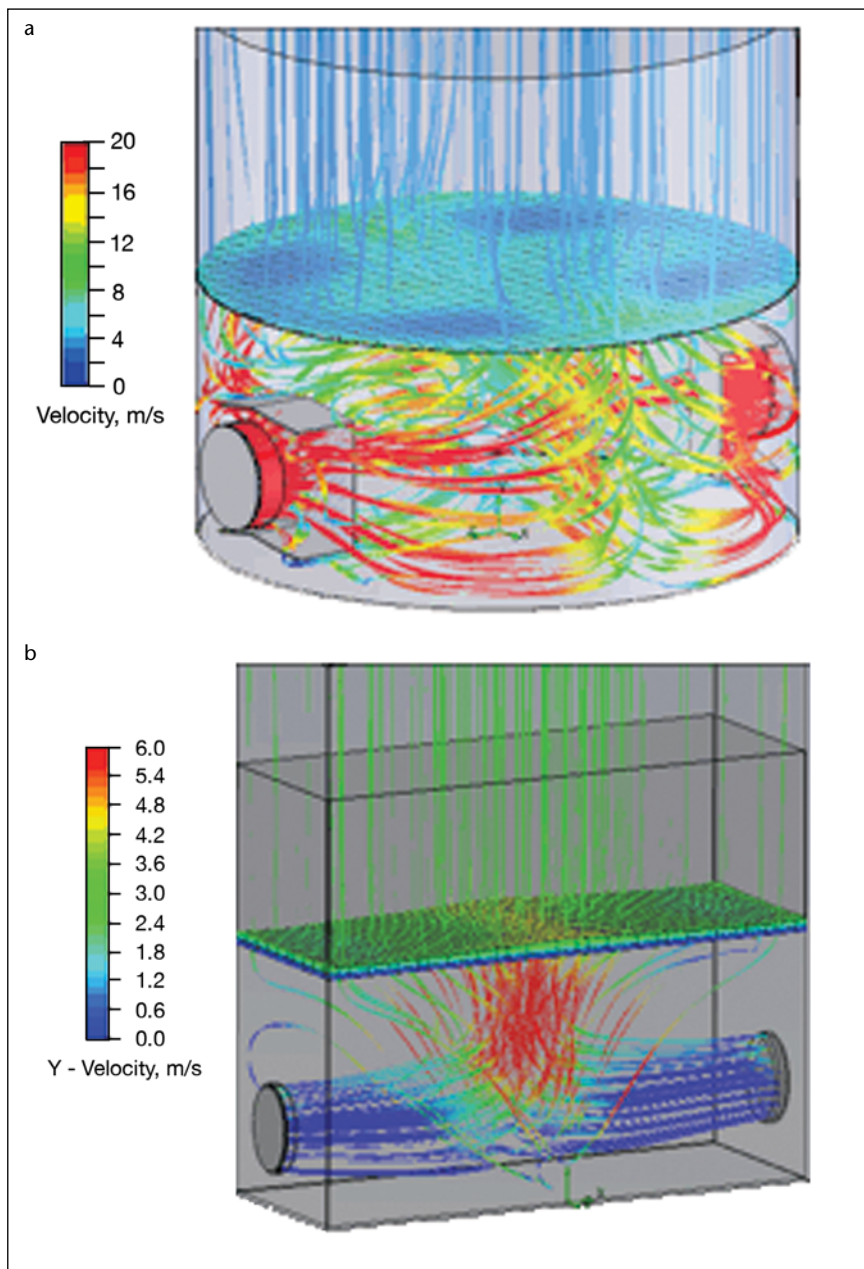


Figure 6 Sulzer vapour distribution configurations: (a) circular (b) rectangular column

vice versa, this is purely an economic trade-off between Capex and Opex, which must be accounted for by the process designer. Also, the liquid and gas distributors must be properly selected, as these are critical in ensuring the successful operation of the packed beds, especially in such large-scale absorbers.

ProTreat is a mark of Optimized Gas Treating, Inc. MellapakPlus is a mark of Sulzer Chemtech AG. M252Y belongs to the MellapakPlus family of structured packing manufactured by Sulzer Chemtech AG, Switzerland. CMR1", CMR1.5", IMTP25 and IMTP40 belong to the random packing portfolio of Koch-Glitsch Inc, USA (www.koch-glitsch.com). Sulcol (SULCOL) is the hydraulic rating tool available from Sulzer Chemtech AG. This article is based on a paper presented at the recent ERTC in Vienna, Austria.

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