Optimization of Gas Velocity and Pressure Drop in CO_2 Absorption Column

Kwangsu Park Lars Erik Øi

Department of and Process Technology, University College of Southeast Norway, Norway

lars.oi@usn.no

Abstract

For a traditional amine-based CO_2 capture system, the absorber column accounts for a significant part of the overall capital- and operating cost. One important design factor of absorber columns is the gas velocity through the absorber packing. Higher gas velocity leads to higher energy cost due to increased pressure drop, but at the same time lower packing cost due to increased effective interfacial area. By utilizing available correlations in the new version 9.0 of the simulation program Aspen HYSYS, the cost optimum gas velocity can be determined. This work evaluated six types of structured packings: Mellapak 250X, 250Y, 2X, 2Y, Mellapak Plus 252Y and Flexipac 2Y. The simulation results show that for all the packings, the cost-optimum gas velocity is in the range of 2.0 to 2.5 m/s giving a pressure drop through the absorber in the range of 10 to 15 mbar.

Keywords: CO_2 absorption, Aspen HYSYS, structured packing, pressure drop

1.1 Introduction

With growing interest in mitigating the level of global CO_2 emissions, carbon capture and storage technology is essential to abate the global warming. The most studied post-combustion method for capturing CO_2 from exhaust gases is to absorb CO_2 into an amine-based liquid solvent. Structured packings are often preferred as vapour-liquid contacting devices, especially because of their high mass transfer area and low pressure drop.

The absorber column internals, especially packing sections, contribute significantly to the overall capital cost of a CO_2 capture plant. The operating cost of the absorber column is dominated by the energy cost to overcome pressure drops across the column. Different structured packing types have different physical and hydraulic properties that will represent advantages and disadvantages depending on the application. The commercial process simulation program Aspen HYSYS V9.0 has built-in correlations to estimate such hydraulic properties, especially pressure drop and effective interfacial area.

Due to high interfacial area and low pressure drop, structured packing is probably the most optimum packing for large scale CO_2 absorption (Øi, 2012). Sulzer Chemtech, Montz and Koch-Glitsch are three well-known suppliers of structured packing. Structured packing types like Mellapak (from Sulzer Chemtech), Flexipac (from Koch-Glitsch) and Montz-Pak (from Montz) have been recommended for large scale CO_2 absorption. Data for Montz-Pak are not available in Aspen HYSYS.

There are few references to calculations or evaluations of optimum gas velocity in the open literature. Sulzer Chemtech has published two papers (Sulzer, 2009; Menon and Duss, 2011) discussing structured packing for CO_2 capture and presenting a new packing type (Mellapak CC-2 and CC-3) especially suited for CO_2 capture. Some conclusions were that structured packing is more cost optimum than random packing, and that high packing efficiency combined with low pressure drop is the key factor for an optimum packing. An assumed gas velocity of 2.1 m/s was suggested (Menon and Duss, 2011). Data for Mellapak CC-2 or Mellapak CC-3 are not available in Aspen HYSYS.

At Telemark University College (now University College of Southeast Norway), Øi (2012) has cost optimized most of the process parameters in a CO_2 capture process in his PhD work. A (superficial) gas velocity in the absorption column of 3.0 m/s was assumed, and this value is probably too high because the cost due to the pressure drop becomes excessively high. Typical values for pressure drop in CO_2 capture absorbers from literature are 10-20 kPa (Øi, 2012).

In his Master Thesis work Amaratunga (2013) performed optimization calculations in order to find the most economical packing type and optimum design parameters. Traditional packing types such as 1 and 2 inch Pall rings (random packing) and Mellapak 250Y (structured packing) were considered. A trade-off between packing cost and cost of pressure drop was performed. A conclusion was that optimum gas velocity was probably between 1.5 to 2.0 m/s.

Paneru (2014) continued this work in his Master Thesis. The work of Paneru was based on measured pressure drops from literature (Zakeri et al., 2012). He concluded that the optimum gas velocity was approximately 2.0 m/s for most packings, and that the optimum pressure drop was about 10 mbar.

For such optimization calculations, estimation methods for pressure drop and effective interfacial area are important. References for estimation of pressure drop and interfacial area in structured packings are de Brito et al. (1994), Billet and Schultes (1999) and Bravo et al. (1985). Effective interfacial area (a_{EFF}) is a traditional way to specify the ratio of the effective gas/liquid mass transfer area to the nominal area.

In capital cost estimation, different data and methods have been used in literature. Equipment cost data from Peters and Timmerhaus have been used in the net calculator (2002) and the program Aspen Icarus have been used. Installation factors have been used to estimate total investment (Paneru, 2014). To calculate operating cost, energy consumption to compensate for the pressure drop has been calculated (Amaratunga, 2013; Paneru, 2014).

This work utilizes Aspen HYSYS simulations including available correlations in "Internal Column Analysis" and cost data to calculate the optimum gas velocity and the optimum pressure drop. The general purpose of the work is to contribute to the cost optimum design of absorption columns for CO_2 capture. A more specific purpose is to show that a combination of process simulation, use of pressure drop correlations and cost estimation is an efficient way to determine the optimum design conditions.

2 Process simulation

2.1 Mass transfer and equilibrium model

The Acid Gas Property Package in Aspen HYSYS® V9.0 was used to simulate the absorption column to absorb CO_2 from a typical exhaust gas from a 400 MW natural gas based combined-cycle power plant.

Figure 1 shows the representation of the absorption column in the simulation program Aspen HYSYS. The inlet amine (lean amine) has a low CO_2 concentration and the outlet amine has a high CO_2 concentration (rich amine).

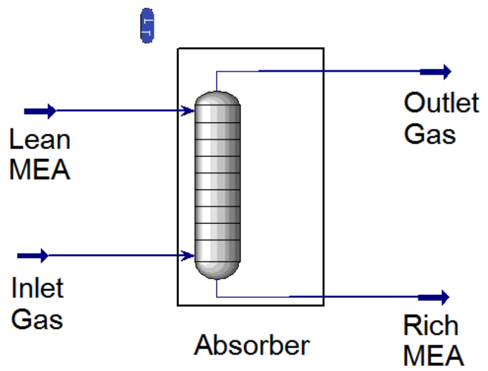

Figure 1. Absorption column in Aspen HYSYS

The rate-based model in Aspen HYSYS considers an individual phase on each stage, and calculates Murphree efficiencies and mass- and energy balances for different packing options. The Electrolyte NRTL thermodynamic model (Austgen et al., 1989) and rate-based simulation was used to model the absorption column. The six types of structured packing evaluated were Mellapak 250X, Mellapak 250Y Mellapak 2X, Mellapak 2Y, Mellapak Plus 252Y and Flexipac HC 2H (2Y). To predict the effective interfacial area and mass transfer coefficient for the different packings, the BRF-85 correlation (Rocha et al., 1985) was used. To estimate column pressure drops, the in-built vendor correlations were used for Mellapak packings. For Flexipak HC 2H, the Aspen-Wallis method was used for pressure drop estimations.

2.2 Specifications and simulation of standard process for CO_2 capture

The specifications used are presented in Table 1. The specification are similar to the specifications in a simulation from Øi (2007).

Table 1. Process simulation input specifications

Parameter	Value
CO_2 removal grade	85.0 %
Inlet gas pressure	40 °C
Inlet gas pressure	1.1 bar
Inlet gas molar flow rate	85000 kmol/h
CO_2 in inlet gas	3.73%
Water in inlet gas	6.71%
Nitrogen in inlet gas	89.56%
Lean MEA temperature	40°C
Lean MEA pressure	1.1 bar
Lean MEA molar flow rate	Varied
MEA content in Lean MEA	29.0 mass-%
CO_2 in Lean MEA	5.5 mass-%
Number of stages in absorber	10

2.3 Simulation procedures

The base case was specified for each type of packing with the gas velocity of 2.5 m/s and the total packed bed height of 10 meter. Based on the inlet gas volume flow and the gas velocity (2.5 m/s), the required absorber column diameter was calculated. The lean amine rate was then adjusted so that the absorption efficiency became 85 %. By exporting pressure drops from the absorber column top, a pressure drop across each stage was estimated. The sum of these pressure drops is the absorber column pressure drop. The top stage pressure was specified to be equal to the atmospheric pressure (101.3 kPa). The required inlet gas pressure to overcome pressure drop was determined by adding the estimated pressure drop to the atmospheric pressure. The inlet gas pressure obtained in this step is normally not exactly the same as the initially specified inlet gas pressure. Therefore, the inlet gas pressure was updated by a calculated value. This, in turn, causes a slight change in the column diameter (due to change in actual gas volume flow), absorption efficiency as well as the absorber pressure drop. It is therefore necessary to adjust the lean amine rate, export pressure drops (from the top) and update the inlet gas pressure again. The procedures stated so far have been iterated until there is no notable change in the required inlet gas pressure, absorber column diameter and the absorption efficiency.

For other gas velocities than 2.5 m/s (1.5 m/s, 2.0 m/s and 3.0 m/s), the absorption efficiency of 85% was achieved by adjusting the packed height. The lean amine rate was kept at the same value as in the base case.

For simulation simplification, no static vapour head was considered for pressure drop calculations and pressure drop across the sump was not included.

3 Cost estimation

A total project cost was calculated by considering the equipment installation cost and operating cost. The flue gas fan, absorber column shell, packing and other column internals (liquid distributor, packing support, liquid catcher) were included in estimating the equipment cost. For fans and absorber columns, cost data from Smith (2005) were used. The equipment base size was converted to actual dimensions by using a power law with corresponding cost exponents. The unit cost of structured packings was assumed as 7600 €/m^3 (2010 basis) based on cost data from Dimian et al. (2014). For Mellapak 252Y Plus only, a 50 % higher unit cost was assumed. For column internals, the unit cost was assumed as 4000 \$/m^2 for liquid distributor, 800 \$/m^2 for packing support and 2000\$/m^2 for liquid catcher based on data from Dejanovic (2011). Two separate packed sections were assumed in the absorber column, five stages in the upper and lower part respectively. The purchased cost values were converted to 2016 currency using the CPI index (McMahon, 2017) and then converted to Euro.

An installation factor for each equipment unit was determined based on the purchased equipment cost in carbon steel. To calculate installation costs in stainless steel, an installation factor of 2.87 was used for packings, liquid distributors, packing supports and liquid catchers. These installation factors were based on a table from Nils Eldrup as used by e.g. Øi (2012) with the assumptions that the direct cost factor contains equipment and erection factor only, that the engineering cost factor contains engineering, process and mechanical factor only and that no administration cost is considered.

The material factor of stainless steel was assumed to be 1.75 for all column internals (including packings). The ratio of the installation cost to the purchasing cost is therefore 1.64 (=2.87/1.75). For the flue gas fan in stainless steel, a material factor of 1.3 was used. For absorber column shell (in carbon steel), an installation factor of 4.44 was used.

To allow for the column internals, the absorber column was assumed to have an additional height of 15 meter besides the packing sections. The flue gas fan was specified to have an adiabatic efficiency of 0.75 which is the default efficiency in Aspen HYSYS. This is a reasonable efficiency for a high gas flow. For the full-flow alternative, the gas flow is 85000 kmol/h, and it is assumed that the flue gas fan is designed for a gas flow close to optimum conditions.

To estimate operating costs, a unit electricity cost of 0.05 €/kWh was assumed. The yearly interest rate was specified to be 7.0 %. It was also assumed that the calculation period is 20 years, including one year of construction. The operating time was 8000 hours/year.

4 Results

4.1 Results for optimum gas velocities

The total cost for different gas velocities is distributed on absorber packing, absorber shell, flue gas fan and operating cost (OPEX) in Figure 2, Figure 3, Figure **4**, Figure 5, Figure 6 and Figure 7.

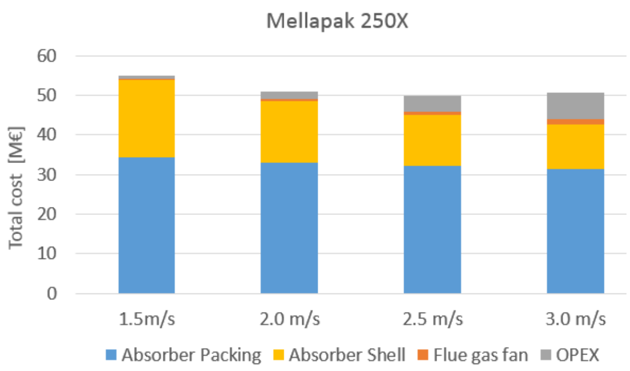

Figure 2. Cost distribution for packing 250X

For Mellapak 250X the optimum is at 2.5 m/s. The gas velocity at 3.0 m/s is close to be optimum. The investment in packing and shell decreases with increasing velocity, while the OPEX is increasing.

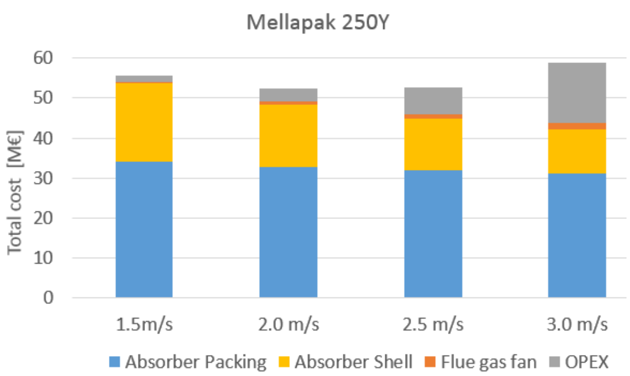

Figure 3. Cost distribution for packing 250Y

For Mellapak 250Y the minimum is at 2.0 m/s, but the gas velocity at 2.5 m/s is close to be optimum. It is seen that with increasing gas velocity, the energy cost increases much more noticeably than with 250 X.

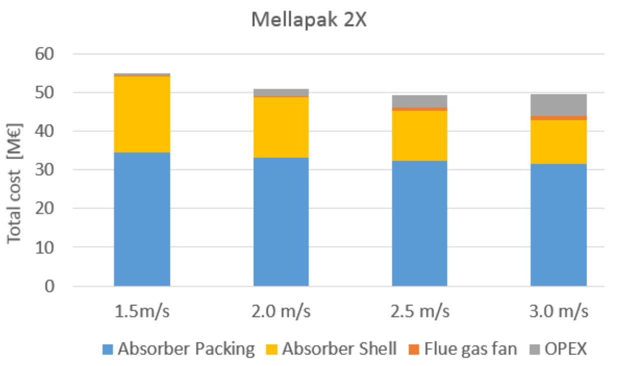

Figure 4. Cost distribution for packing 2X

The results for Mellapak 2X are highly similar to the results for 250X. The optimum is at 2.5 m/s but 3.0 m/s is close to be optimum.

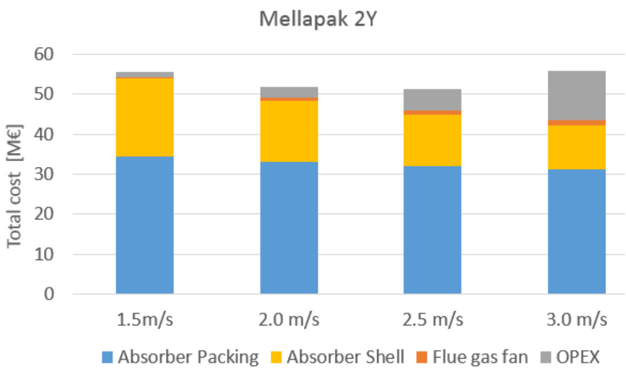

Figure 5. Cost distribution for packing 2Y

The results for Mellapak 2Y are very similar to the results for 250Y. However, for 2Y, the minimum total cost is achieved for 2.5 m/s, and 2.0 m/s is quite close to be optimum.

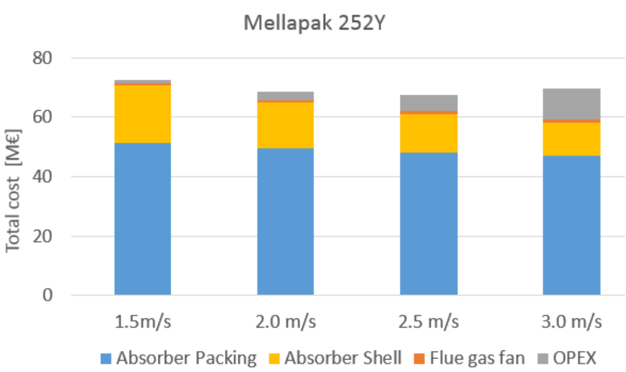

Figure 6. Cost distribution for packing 252Y

For Mellapak 252Y the energy cost is increasing only slightly with gas velocity. The optimum gas velocity is 2.5 m/s.

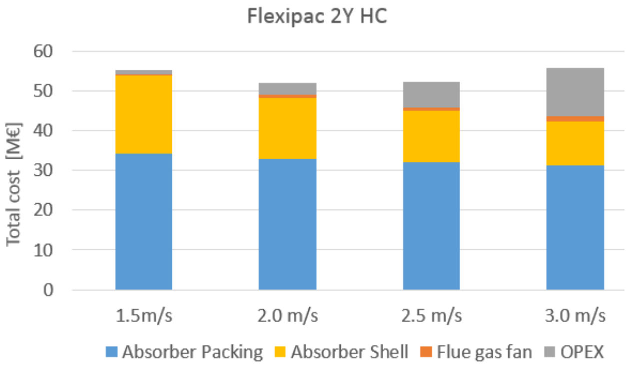

Figure 7. Cost distribution for packing Flexipac 2Y HC

For Flexipac 2Y HC, the optimum appears at 2.0 m/s. The results for Mellapak 250Y and Flexipac 2Y HC are very similar. For all packing types, the lowest total cost and then the optimum gas velocity was achieved at 2.0 or 2.5 m/s.

4.2 The results for optimum pressure drop

Figure 8 shows the pressure drop (per meter of packed bed) according to the type of packing and the gas velocity at the conditions in Figures 2 to 7. The packing with the lowest pressure drop is Mellapak 2X, followed by 250X. The Y type packings have higher pressure drop, and this becomes more clear at higher gas velocities. The special packing Mellapak 252Y has less increased pressure drop at higher gas velocities.

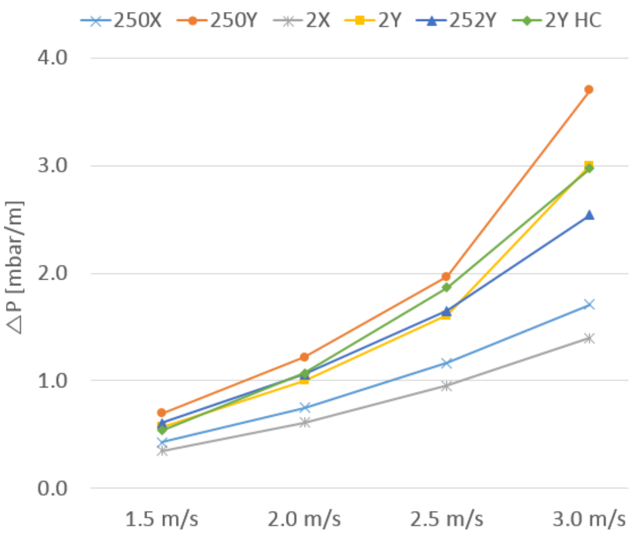

Figure 8. Pressure drop as a function of gas velocity for the different packings

Table 2 shows the optimum absorber pressure drop at the optimum velocity for each type of packing. The optimum pressure drop was calculated by combining the number of absorber stages, unit packing pressure drop [mbar/m] and the unit packing height [m/packing].

Table 2. Optimum gas velocity and pressure drop for different packings

	Optimum v [m/s]	Optimum ΔP [mbar]
Mellapak 250X	2.5	11.7
Mellapak 250Y	2.0	10.0
Mellapak 2X	2.5	9.5
Mellapak 2Y	2.5	16.1
Mellapak 252Y	2.5	16.5
Flexipac 2Y HC	2.0	8.7

4.3 Optimization including maintenance cost

An alternative calculation was performed including maintenance as a part of the operating cost. The yearly maintenance cost was specified to 3 % of the total investment and is a value in the lower range of recommended values (Smith, 2005). A low value is assumed because the investment of the absorption process is assumed to be high compared to the complexity. Including maintenance cost into the total cost does not affect the pressure drop data which were obtained from the Aspen HYSYS simulation.

The calculated optimum velocity was in most cases not changed. But for Mellapak 250Y the optimum velocity increased to 2.5 m/s and for Mellapak 2X the optimum gas velocity increased to 3.0 m/s. This is because including maintenance cost slightly increases the influence of the investment while there is no change in the operating cost. Overall, the maintenance cost does not have significant influence on determining the optimum velocity.

5 Discussion

The cost estimates are of course highly sensitive to changes in packing cost, change in calculation time (years of operation) and change in power cost. All these specifications have a large uncertainty. When optimizing the gas velocity and pressure drop, the optimum gas velocity (and then the optimum pressure drop) are however quite stable for a large range of the cost parameter values. This was also the experience in the work of Amaratunga (2013) and Paneru (2014). The calculation including maintenance as a part of the operating cost also shows that the optimum conditions are not influenced much by changing the cost parameters.

The uncertainty in cost data for structured packing including installation cost is high. The uncertainty in the cost of liquid distribution and gas distribution equipment is also high. This is because these cost data are based on information from suppliers, and there is not much open information from the suppliers available.

The performance data of structured packings officially published by suppliers (Sulzer, Koch-Glitsch or Montz) may be overestimated or underestimated. The discrepancy between the supplier's correlations and experimental data becomes clearer when the pressure drop is measured at wet conditions compared to dry conditions (Zakeri et al., 2012). This might have caused the deviations between the results in Paneru (2014) compared to the results in this study.

The deviations in estimated effective interfacial area are assumed to be of less importance compared to the deviations in estimated pressure drop (Øi, 2012).

The optimum pressure drops in this work are in the same range as in the earlier works. The values of optimum gas velocities in this work are between the values reported in Øi (2012) which are higher (3.0 m/s), and Amaratunga (2013) and Paneru (2014) which are lower (from below 2.0 m/s to 2.5 m/s).

A low-pressure type of packing is the type with curved ends like in Mellapak Plus 252Y from Sulzer Chemtech. Other suppliers like Koch-Glitsch and Montz also have such types of packing. The curved-end packings are however not much different in pressure drop at normal gas velocities. Lower pressure drop for curved packings is achieved at high gas velocities that are not cost optimum conditions for any of the packings. Assuming a cost for the Mellapak Plus 252Y packing 50 % higher than other packings, Mellapak Plus 252Y was found not to be cost optimum.

Sulzer Chemtech also has the packing types Mellapak CC-2 and CC-3 especially developed for CO_2 capture. The suggested gas velocity of 2.1 m/s by Sulzer (Menon and Duss, 2012) is within the range of optimum gas velocities in this work. The cost of a commercial specialized packing has high uncertainty because of the possibility for the supplier to adjust the price according to the market conditions. Because of this, it is very difficult to evaluate generally whether a specialized packing is cost optimum.

6 Conclusion

Optimum gas velocity and pressure drop have been determined for different structured packings utilizing Aspen HYSYS simulation and cost estimation.

The calculated results show that the optimum gas velocity lies in the range of 2.0 to 2.5 m/s for all the six structured packings. The corresponding pressure drops through the absorber packing were in the range of 10 to 15 mbar. There is a large uncertainty in cost data, especially in the cost of purchase and installation of structured packing and other column internals. Alternative calculations show that this uncertainty in cost data has only a limited influence on determining the optimum gas velocity and pressure drop.

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