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Simulation and optimization of a flue gas dryer at industrial scale using a temperature swing adsorption

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The majority of recent studies on carbon capture from industrial flue gases have focused on the separation of carbon dioxide mainly from nitrogen. Hence, water has generally been omitted in discussions, despite being one of the main products of combustion (≈ 7-10%mol [1]). Yet wet gases may be extremely detrimental to adsorption processes with a decrease in CO_2 adsorption capacity, and even incapacitating for cryogenic capture. Ultimately, CO_2 transportation and storage conditions require less than 30 ppm mol of water, which leads to a dehumidification unit, regardless of the carbon capture process involved [2]. For an accurate and proper evaluation of a complete greenhouse gas capture chain, it is essential to consider the impact of an industrial dryer. Therefore, for an accurate and proper evaluation of a complete greenhouse gas capture chain, it is therefore essential to consider the impact of an industrial dryer. In this context, separation is commonly achieved either through adsorption or membrane technology. Although the latter has a higher technology readiness level, it presents more complex upscaling challenges, with a very large footprint to reach low humidity target. Moreover, the long-term stability of membranes in the presence of water and other corrosive compounds (CO_2, O_2, SO_x, …) is not well understood, which represents an additional barrier to their use [3]. While adsorption thus seems to be a promising alternative, publications on the drying of post-combustion gases at an industrial scale are still scarce.

A TSA dryer could be integrated as pre-treatment unit in carbon capture chain for instance dryer for dehumidification, followed by pre-concentration via adsorption (VPSA), and capture by cryogenics [4] as illustrated in figure 1. The coupling offers the advantage of reusing low-interest gases from the other two units (rich in nitrogen and low in carbon dioxide) for the regeneration of the columns through TSA. This approach avoids the two conventional methods of using either part of the dry gas exiting the dryer (which is rich in CO_2) or heated humid air. Due to the adsorption competition between water and carbon dioxide in the VPSA and the risk of condensation in the cryogenic unit, a maximum residual absolute humidity of 1 ppm mol was set.

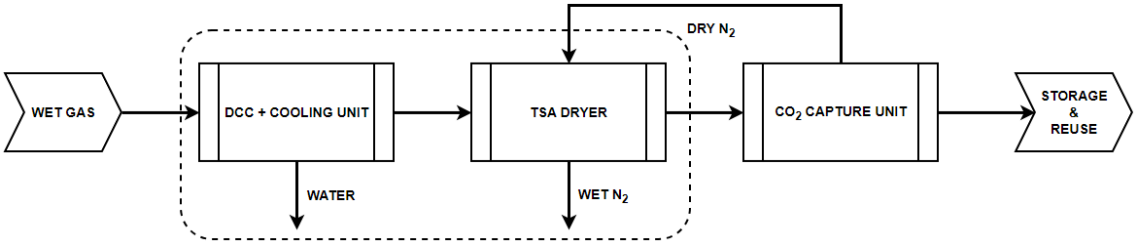

Figure 1. Flowsheet of the bloc chain treatment for the CO_2 capture

An industrial scale Temperature Swing Adsorption (TSA) process for the treatment of post-combustion gases has then been developed using the gPROMS software. Additionally, two types of adsorbents, commonly used in industrial drying, were compared. These are a silica gel from the BASF group (Sorbead R2050) and a commercial activated alumina from Brownell (F200). Both present the advantage of having medium to low regeneration temperatures (100-200°C and 150-250°C, respectively). For industries where available waste heat is at low temperature, silica gel is the best candidate, whereas activated alumina shows slightly better performance and chemical stability but at the cost of more expensive regeneration. Their kinetic and thermodynamic parameters were measured experimentally using BET method, breakthrough curve and adsorption isotherm (on N_2, CO_2 and H_2O) measurements.

A good representation of mass transfer is essential for an adequate modelling of the process; therefore, a comprehensive and detailed study was conducted, simultaneously combining both experimental and theoretical approaches. It is based on the measurement of uptake curves of a sample using gravimetric or volumetric equipment under various conditions. A mass transfer coefficient, dependent on temperature and pressure, was measured for water and carbon dioxide, and the main contributing mechanism for transport within the pores of the adsorbent was deducted by theoretical models. The obtained values enable the generation of simulated breakthrough curves, which are then validated against those obtained experimentally. The measurements demonstrate behaviour consistent with an Arrhenius law with respect

to temperature and a parabolic effect with partial pressure, as previously observed for this type of interaction [5].

Finally, a parametric study was conducted to determine the optimal operating conditions and the influence of these parameters on the system's performance. Various TSA cycles and configurations were selected with a common base of having three main steps (adsorption, heating and cooling) [6-7].

The inlet flow rate was set at 70,000 Nm^3/h, which corresponds to a typical value for an industrial process (e.g. the production of 1000T/day of clinker in cement industry [4]). Different sizes and geometry of the units required to process such a flow rate were considered and optimized while maintaining a length-to-diameter ratio (L/D) between 2.5 and 5, as well as a superficial velocity between 50 to 80% of the minimal bed fluidization velocity. The time for each step has also been optimized from adsorption [5-15 hours], heating [4-10 hours], and cooling [4-10 hours]. The flow rate associated with the regeneration steps was also studied from 4000 to 10 000 Nm^3/h for both heating and cooling. Next, the CO_2 concentration was investigated over a range of 5 to 20%, with the relative humidity maintained at 100%. Since the water content is dependent on temperature, the latter varied from 20 to 40°C. Additionally, the heating step temperature ranged from 100 to 200°C, while the cooling temperature was fixed at 25°C. Finally, given the exponential variation of the water saturation vapor pressure with temperature, it appears that pre-cooling the flue gas to remove a significant portion of the water is crucial for process design. This objective led to the development of a direct contact cooler process in Aspen Plus.

At the conclusion of the parametric study, it appears that one of the most optimal configurations would involve three units, each processing 23,333 Nm^3/h with an adsorption time of 10 hours. Each unit is composed of three beds, with two in adsorption and one in regeneration as depicted in figure 2. The heating phase would last 5 hours and 30 minutes at a flow rate of 7,000 Nm^3/h and a temperature of 170°C. Subsequently, cooling would take place over 4 hours and 30 minutes with a flow rate similar to that of heating. Finally, it was found that a flue gas temperature above 40°C results in an oversized TSA system, while temperatures below 20°C would require a different refrigeration system for the DCC, significantly increasing costs. Therefore, the optimum temperature is estimated to be between 20 and 25°C which leads to an energy consumption of 4.3MJ/kg of water removed.

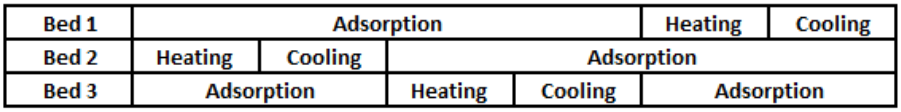

Figure 2. Industrial three columns and three step simulated temperature swing adsorption for gas drying

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