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Impact of kiln thermal energy demand and false air on cement kiln flue gas CO_2 capture

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Abstract
The present study is focused on the effect of the specific thermal energy demand and the false air factor on carbon capture applied to cement kiln exhaust gases. The carbon capture process model was developed and implemented in Aspen Plus. The model was developed for flue gases from a typical cement clinker manufacturing plant. The specific thermal energy demand as well as the false air factor of the kiln system were varied in order to determine the effect on CO_2 capture plant performance, such as the solvent regeneration energy demand. In general, an increase in the mentioned kiln system factors increases the regeneration energy demand. The reboiler energy demand is calculated as 3270, 3428 and 3589 kJ/kg clinker for a specific thermal energy of 3000, 3400 and 3800 kJ/kg clinker, respectively. Setting the false air factor to 25, 50 or 70% gives a reboiler energy demand of 3428, 3476, 3568 kJ/kg clinker, respectively.

Keywords: Carbon dioxide capture; Cement; Flue gas; MEA; Reboiler duty.

1. Introduction
The emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) need to be reduced in order to reduce global warming. The main sources of CO_2 emissions are power plants (coal and gas), the transport sector (burning fuel) and chemical industries (cement and aluminium). The most well established CO_2 capture technology is chemical absorption, in which CO_2 is absorbed in a solvent, such as an amine solution. The weak base amines are reacting chemically with CO_2 to form new chemical compounds. However the bonds are relatively weak, and therefore quite easily broken in a heating process [1]. Hence, the solvent can be regenerated in a desorber and then re-used in the absorber.
CO_2 capture related to the power plants has been in focus for some years. However, capture of CO_2 in the cement kiln process has not been widely considered. A model was previously developed for cement kiln flue gas CO_2 capture by the current authors [2]. A simple flowsheet illustrating a cement kiln system with CO_2 capture is shown in Figure 1.
The present study will focus on the impact of variable flue gas composition, due to variable kiln process energy demand and variable false air ingress, on the energy demand of the CO_2 capture process, more specifically on the required regeneration energy in the desorber.

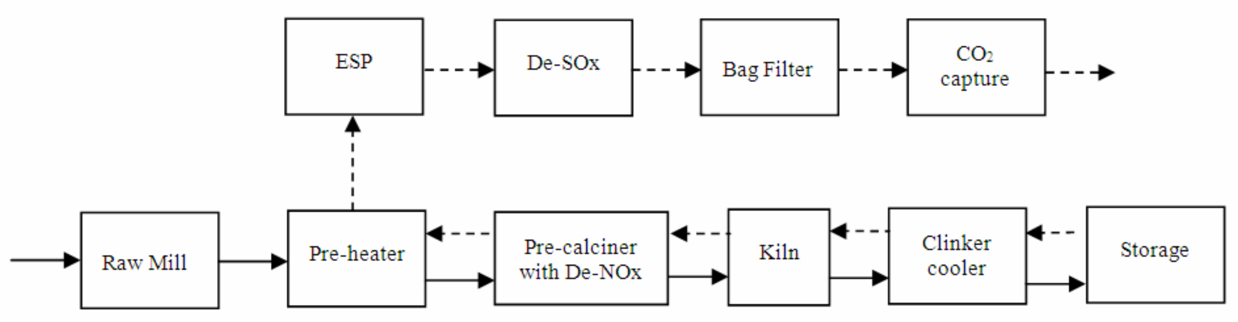

Figure 1. Cement plant with CO_2 capture unit

2. Model development

The schematic of a typical flue gas capture plant is shown in Figure 2. A detailed description of this process is given in a previous publication [3]. The flue gas leaving the upstream process is around 80°C and has to be reduced to 40°C before entering the capture process in order to improve the performance of the chemical absorption.

The flue gas composition is calculated for a generic cement manufacturing plant producing 1 Mt clinker per year and using coal as the thermal energy source (Table 1). The base case represents a typical modern precalciner cement kiln system, with a typical specific thermal energy demand of 3400 MJ/$kg_{clinker}$ and 25 % false air ingress, giving a typical exhaust gas composition and flow rate.

However, the exhaust gas composition (and flow rate) will be different if the specific thermal energy consumption of the kiln system is different. For example, the energy consumption may increase if the raw mix reactivity is low, meaning that more fuel will have to be combusted in order to give the same product quality [4]. Hence, to investigate the impact of the kiln energy demand on the CO_2 capture process, the specific thermal energy demand of the kiln system is varied from a very low value (3000 MJ/$kg_{clinker}$) to a value which is quite high (3800 MJ/$t\_{clinker}$) but still within a range that can be experienced in the cement industry.

The exhaust gas entering the capture plant will also be different if the the false air ingress in the preheater tower (and possibly also in downstream process equipment) is different. The false air ingress is due to the combination of under pressure operation (practically all modern kiln systems are operated with a suction) and unwanted leakage points in the preheater construction or in other process equipment units.Hence, in this study, the false air inleakage factor is varied from the base value via an intermediate value (50 %) to a very high value (70 %).

Collected and calculated data related to the cement manufacturing process are given in Table 1.

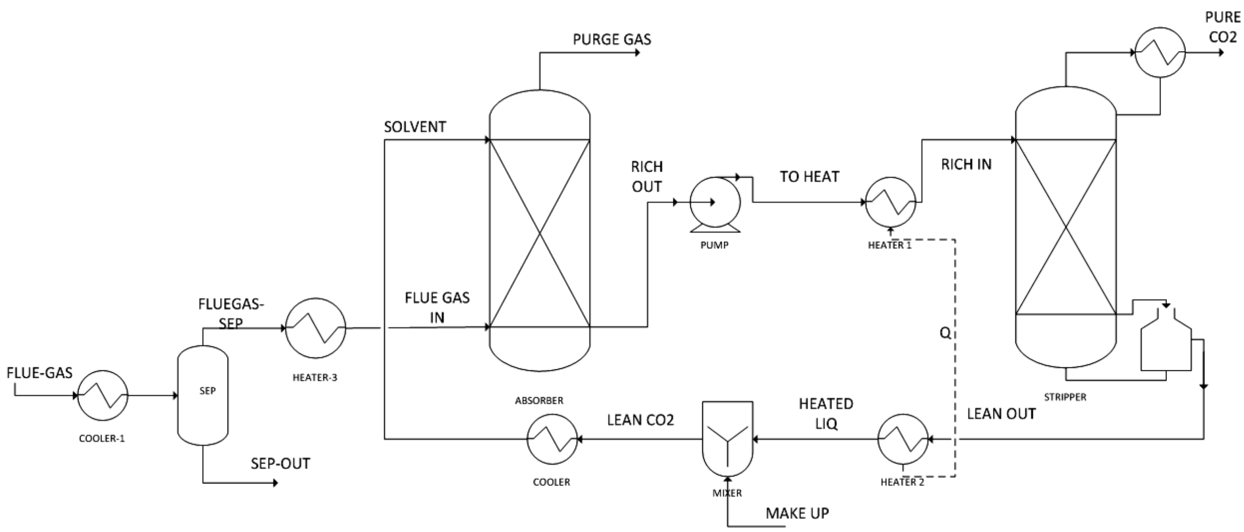

Figure 2. Process flow diagram

Table 1. Parameter values for the cement manufacturing process

			Specific thermal energy demand			False air factor		
Description	**Unit**	**Base case**	**3000 MJ/t_cli**	**3400 MJ/t_cli**	**3800 MJ/t_cli**	**25 %**	**50 %**	**70 %**
Clinker production rate	t/y	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
Fuel heating value	MJ/kg_fuel	27.7	27.7	27.7	27.7	27.7	27.7	27.7
Run factor	-	85%	85%	85%	85%	85%	85%	85%
C in fuel	wt%	71.8 %	71.8 %	71.8 %	71.8 %	71.8 %	71.8 %	71.8 %
H in fuel	wt%	3.9 %	3.9 %	3.9 %	3.9 %	3.9 %	3.9 %	3.9 %
O in fuel	wt%	5.9 %	5.9 %	5.9 %	5.9 %	5.9 %	5.9 %	5.9 %
S in fuel	wt%	1.2 %	1.2 %	1.2 %	1.2 %	1.2 %	1.2 %	1.2 %
N in fuel	wt%	1.7 %	1.7 %	1.7 %	1.7 %	1.7 %	1.7 %	1.7 %
Ash in fuel	wt%	14.4 %	14.4 %	14.4 %	14.4 %	14.4 %	14.4 %	14.4 %
Moisture in fuel	wt%	1.2 %	1.2 %	1.2 %	1.2 %	1.2 %	1.2 %	1.2 %
O2 demand	kg/kg_fuel	2.18	2.18	2.18	2.18	2.18	2.18	2.18
Specific air demand (stoich.)	kg/kg_fuel	9.3	9.3	9.3	9.3	9.3	9.3	9.3
Specific air supply	kg/kg_fuel	10.3	10.3	10.3	10.3	10.3	10.3	10.3
Run time	h/y	7,446	7,446	7,446	7,446	7,446	7,446	7,446
Fuel consumption	t/h	16	15	16	18	16	16	16
Air supply	t/h	170	150	170	189	170	170	170
N2	Nm³/h	122,552	109,300	122,552	135,805	122,552	159,115	232,240
CO2	Nm³/h	59,708	57,109	59,708	62,306	59,708	59,708	59,708
H2O	Nm³/h	7,200	6,353	7,200	8,047	7,200	7,200	7,200
O2	Nm³/h	7,374	6,816	7,374	7,932	7,374	17,093	36,531

The specific thermal energy of the kiln system, E [MJ/t_$_{clinker}$], is the product of fuel flow rate ($m_{fuelmix}$ [kg/s]) and fuel heating value ($H_{fuelmix}$ [MJ/kg]) divided by the clinker production rate ($m_{clinker}$ [kg$_{clinker}$/s]):

$$E = \frac{m_{fuelmix} H_{fuelmix}}{m_{clinker}} \tag{1}$$

The false air factor, r_{false}, is the ratio of the false air flow rate, V^n_{false} [Nm³/h], and the flow of false air and kiln flue gas upstream of the kiln, V^n_{kiln} [Nm³/h]:

$$r_{false} = \frac{V^n_{false}}{V^n_{false} + V^n_{kiln}} \tag{2}$$

Post combustion chemical absorption means using a solvent that has the capacity to absorb acidic gases (CO_2). The monoethanolamine (MEA) is the most prominent solvent that has been tested on pilot plants and is often used for experiments. MEA is a primary alkanolamine, R-NH_2, where R represents the alkyl group. The rate of reaction as well as the required heat for regeneration are crucial factors for selecting the solvent. The heat of absorption of CO_2 by MEA is considerably high. At the same time, MEA is characterized by a relatively high degradation rate, and it has a limited lean CO_2 loading. Even though MEA shows those drawbacks, it is considered as the reference solvent for CO_2 capture process. The reason for that is that a low partial pressure of CO_2 in the flue gas (typical of power plants as well as many industrial processes) can be handled due to the high reactivity of MEA towards CO_2 [5, 6].

The solvent concentration and lean CO_2 loading in the inlet solvent stream are selected as 30 wt% and 0.3 mol CO_2/mol MEA, respectively. In the CO_2 capturing process, typically primary and secondary amines form carbamate species (RNH^+COO^-) while reacting with CO_2. The basic reactions related to the absorption and stripping process follow the common style given in equation 3-4 [7]. Here, R indicates an alkyl group in primary amines.

$$CO_2 + RNH_2 \leftrightarrow RNH_2^+COO^- \tag{3}$$

$$RNH_2^+COO^- + RNH_2 \leftrightarrow RNH_2COO^- + RNH_2^+ \tag{4}$$

The type of packing and dimensions of packing material are important. Packed columns are used for the model development according to the previous studies. The Mellapak-Sulzer 350 Y is selected for the absorber, and Flexipak-1Y for the stripper, according to previous studies [8]. The most suitable column specification for model development is given in the Aspen Plus documentation [9] and in a quite recent PhD thesis [10].

3. Simulations

The Aspen Plus process simulation tool is used for the simulation studies. A base case model was first developed in Aspen Plus using data given in the base case column of Table 1. Then, four more cases were calculated, using data from the other columns of Table 1.
The absorber column configurations are selected according to the superficial gas velocity. By maintaining a superficial gas velocity in the absorber column of 2-3.5 m/s, flooding inside the column is avoided. The flue gas conditions that are used for the simulation studies are given in Table 2 (the percentages are based on the flow rate values given in Table 1).

Table 2. Flue gas stream parameters used for the simulations

			Specific thermal energy demand			**False air factor**		
Description	**Unit**	**Base Case**	**3000 MJ/t_cli**	**3400 MJ/t_cli**	**3800 MJ/t_cli**	**25 %**	**50 %**	**70%**
Preheater exhaust gas	Nm³/h	196,834	179,578	196,834	214,090	196,834	243,116	335,679
N_2	vol%	62.3 %	60.9 %	62.3 %	63.4 %	62.3 %	65.4 %	69.2 %
CO_2	vol%	30.3 %	31.8 %	30.3 %	29.1 %	30.3 %	24.6 %	17.8 %
H_2O	vol%	3.7 %	3.5 %	3.7 %	3.8 %	3.7 %	3.0 %	2.1 %
O_2	vol%	3.7 %	3.8 %	3.7 %	3.7 %	3.7 %	7.0 %	10.9 %
Temperature	°C	80						
Pressure	bar	1						

The model is developed for 90% CO_2 removal efficiency. The solvent flow rate is varied to achieve exactly this removal efficiency for every case. The relevant flue gas composition and total flue gas flow rate are inserted for each simulation according to Tables 1 and 2.
Table 3 shows the parameter values for calculating superficial gas velocity inside the absorption column. For every simulation case, the diameter of the absorber column is maintained at 6m. Keeping the absorber column diameter constant and changing the superficial gas velocity is equivalent to allowing for a variation in the flue gas flow rate from the cement kiln while using the same (existing) capture equipment. Anyway, the simulations showed that the energy consumption of the fan downstream of the absorption column is almost negligible (< 1MW) compared to reboiler energy demand, even if the superficial gas velocity is incresed ,so the effect of flow rate on the fan power is actually not necessary to consider.
The regeneration energy demand and the solvent recirculation rate are given in Table 4. The required reboiler energy demand per kg CO_2 and per kg clinker is calculated.
Another set of simulations is performed for using a constant superficial gas velocity and instead adjusting the column diameter (Table 5). The simulated results are given in Table 6. The main idea of maintaining a constant superficial gas velocity is to obtain the same pressure drop over the absorber column in every case. This approach is more relevant in a design phase, when the equipment is still not in place. The column diameter is selected according to a superficial gas velocity of 2.52 m/s, which is within a velocity range 2-3.5 m/s, which can be considered as a typical operational range of packed absorption towers.

Table 3. Inlet gas conditions

			Specific thermal energy demand			False air factor		
Description	**Unit**	**Base Case**	**3000 MJ/t_cli**	**3400 MJ/t_cli**	**3800 MJ/t_cli**	**25 %**	**50 %**	**70%**
Preheater exhaust gas at 80°C	Nm³/h	196,834	179,578	196,834	214,090	196,834	243,116	335,679
	m³/h	254483	232172	254482	276792	254482	314319	433992
Preheater exhaust gas at 40°C	m³/h	207671	189462	207671	225880	207671	256524	354226
Absorber diameter	m	6	6	6	6	6	6	6
Superficial velocity	m/s	2.04	1.86	2.04	2.22	2.04	2.52	3.48

Table 4. Regeneration energy demand with constant absorber packing diameter

			Specific thermal energy demand			False air factor		
Description	**Unit**	**Base Case**	**3000 MJ/t_cli**	**3400 MJ/t_cli**	**3800 MJ/t_cli**	**25 %**	**50 %**	**70%**
Reboiler duty	MW	107.7	102.5	107.7	113.2	107.7	110.2	113.1
Amount of CO_2 captured	kg/s	29.2	28.0	29.2	30.6	29.2	29.3	29.3
Specific Reboiler duty	kJ/kg CO_2	3679	3655	3679	3700	3679	3753	3853
	kJ/kg clinker	3399	3233	3399	3571	3399	3476	3566
Solvent flow rate	tonne/hr	2770	2633	2770	2912	2770	2840	2927

Table 5. Inlet gas conditions and superficial gas velocity

			Specific thermal energy demand			False air factor		
Description	**Unit**	**Base Case**	**3000 MJ/t_cli**	**3400 MJ/t_cli**	**3800 MJ/t_cli**	**25 %**	**50 %**	**70%**
Preheater exhaust gas at 40°C	m³/h	207671	189462	207671	225880	207671	256524	354226
Absorber diameter	m	5.4	5.15	5.4	5.63	5.4	6	7.05
Superficial velocity	m/s	2.52	2.52	2.52	2.52	2.52	2.52	2.52

Table 6. Regeneration energy demand with equal superficial gas velocity

			Specific thermal energy demand			False air factor		
Description	**Unit**	**Base Case**	**3000 MJ/t_cli**	**3400 MJ/t_cli**	**3800 MJ/t_cli**	**25 %**	**50 %**	**70%**
Reboiler duty	MW	108.7	103.7	108.7	113.8	108.7	110.2	113.2
Amount of CO_2 captured	kg/s	29.2	28.0	29.2	30.6	29.2	29.3	29.3
Specific Reboiler duty	kJ/kg CO_2	3710.3	3697	3710	3719	3710	3753	3855
	kJ/kg clinker	3428	3270	3428	3589	3428	3476	3568
Solvent flow rate	tonne/hr	2795	2665	2795	2928	2795	2840	2925

The reboiler energy demand variation with those factors is shown in Figure 3. As can be seen from the figures, the regeneration energy is increasing with in increase in both factors (specific thermal energy and false air factor). However, the value of the regeneration energy demand increment with specific thermal energy demand is more or less negligible; the reboiler duty increases with only 0.4 % when increasing the thermal energy demand from 3000 to 3800 MJ/t$_{_clinker}$. The reason why the impact is so small is that the CO_2 concentration in the flue gas inlet stream is almost the same in all cases. However, the thermal energy demand of the kiln system will affect the size of the absorption column, and hence have an impact on the investment costs.

The false air factor has more impact on the regeneration energy. An increase in false air from 25 to 70 % gives a reboiler duty increase of about 4 %, which is not negligible. The reason for this more severe impact is that the total gas flow rate drastically increases with an increase in the false air factor. Accordingly, the amount of gas that has to be purified in the capture plant increases.

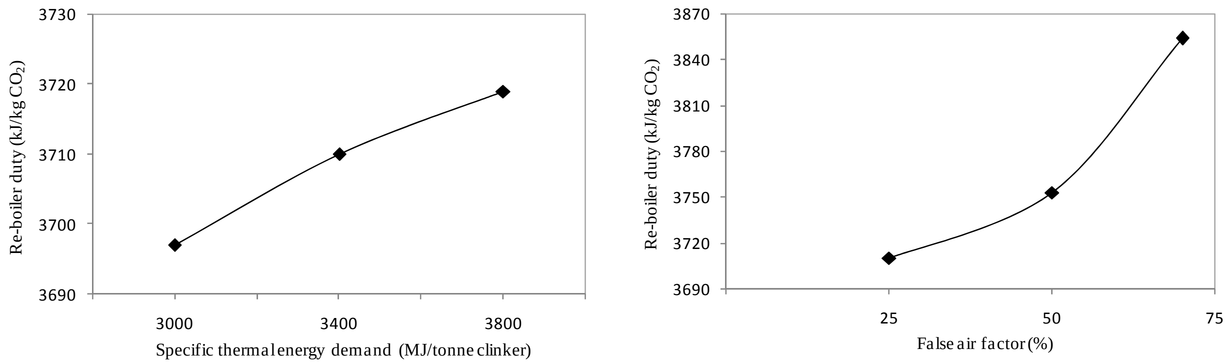

Figure 3. Reboiler duty variation with parameters; Left hand side figure is Re-boiler duty variation with specific thermal energy demand and right hand side is Re-boiler duty variation with false air factor

4. Conclusion

The simulations showed that a variation in specific thermal energy demand of the kiln process within a relatively wide range, applicable to real cement kiln systems, does not give a substantial impact on the operation of the CO_2 capture plant. However, increasing the false air ingress in the kiln system preheater from 25 to 70 % results in a 4 % increase in the reboiler duty. This indicates that false air ingress, which is a well-known phenomenon in the cement industry, should be kept low in order to reduced the energy consumption of the CO_2 capture plant. If, alternatively, the dimension of the absorber column in the capture plant is increased to allow for the higher gas flow rate resulting from an increase in thermal energy demand or false air, then that will lead to increased capital costs when constructing the capture plant. Hence, also for this reason, the false air ingress in the kiln system should be minimized.

Nomenclature

m	mass flow rate [kg/s]
V^n	normal volumentric flow rate [Nm³/h]
H	lower heating value [MJ/kg]

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