Technical Assessment of Efficient Steam Recovery from Alumina Calcination for Sustainable Bauxite Digestion

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Abstract

This study presents a technical analysis of steam cleaning and recovery from the calcination process as a means of decarbonization and energy conservation in alumina refining. Steam recovery is highest from H_2 in oxygen-steam (oxy-steam) calcination (Scenario 4) yielding 0.86 t steam/t Al_2O_3, meeting 43 % of steam demand in digestion based on a reference usage of 2 t steam/t Al_2O_3. In a fully electrified calciner (Scenario 3), the calculated steam recovery is 0.64 t steam/t Al_2O_3, followed by natural gas/air calcination (Scenario 1) and hydrogen/air calcination (Scenario 2), at 0.54–0.55 t steam/t Al_2O_3. Recovering high-purity steam in H_2 in oxy-steam or fully electrified calcination demonstrates higher energy efficiency, consuming 0.54 GJ/t steam energy, with 9% allocated to gas cleaning. In contrast, recovering steam from air-based calcination exhibits lower energy efficiency, requiring 0.71 GJ/t steam energy due to the N_2 dilution in exhaust steam, of which 5 % is attributed to gas separation and cleaning. The calculated energy consumption in digestion decreases by 36 %, from 6.63 to 4.25 GJ/t Al_2O_3, when incorporating steam recovery from H_2 in oxy-steam calciner, compared to solely relying on natural gas boilers. Furthermore, CO_2 emissions for digestion steam generation are expected to reduce by 43 %, from 0.37 to 0.21 t CO_2/t Al_2O_3. Zero carbon emissions in digestion can be achieved by replacing gas boilers with electric boilers and integrating with calcination steam recovery, yielding an additional 15 % energy consumption reduction due to the higher efficiency of electric boilers.

Keywords: Steam cleaning, Efficient steam recovery, Decarbonizing digestion

1. Introduction

In the digeston step of the Bayer process, gibbsitic type bauxite ores are leached in a concentrated NaOH solution under steam temperature of 175–230 °C and pressures of 6–13 bar in low-temperature digestion [1–3], consuming approximately 60–70 % of the total energy consumption (10.5 GJ/t Al_2O_3 in average) in current refineries [4]. This steam is primarily generated from natural gas boilers, which is estimated to emit 0.28–0.64 t CO_2/t Al_2O_3 [5]. Accordingly, decarbonizing the process and achieveing energy conservation are both essential. Instead of generating steam from fossil fuels, energy can be conserved by recovering generated steam from gibbsite decomposition, moisture evaporation and fuel combustion during the calcination. However, the steam is diluted with combustion products and is currently vented to the atmosphere, along with its latent energy [6]. Capturing and reusing it in digestion offers a potential to reduce fossil fuel reliance in steam generation and lower overall energy use in digestion.

The conventional calcination process under natural gas/air combustion releases approximately 0.7 t steam/t Al_2O_3, which contains 1.7 GJ/t Al_2O_3 of latent energy [7]. While the exhausted steam is diluted with N_2 and CO_2, complicating the recovery process. Chatfield [5] proposed using a wet scrubber to condense steam from the flue gas to separate N_2 and CO_2, followed by generating low-pressure steam in flash tanks. However, the study does not quantify the amount of recoverable steam or the energy efficiency of the process. This configuration could also be applied to H_2 in air combusted calcination, where the exhaust steam is diluted with ~50 % N_2. In contrast, H_2 in oxygen-steam (oxy-steam) combustion produces high purity steam, with an estimated amount of 0.8 t steam/t Al_2O_3 [8]. Similarly, a fully electrified calcination system eliminates fuel combustion and produces 0.63 t steam/t Al_2O_3 of pure steam. These two decarbonized calcination pathways simplify steam recovery process due to the absence of N_2 and CO_2. Nevertheless, fine particulates in the flue gas pose a technical barrier. Despite the availability of existing particulate control systems such as Electrostatic Precipitator (ESP), or baghouses that remove solid concentrations to below 50 mg/m^3 (typically ranging from 29 to 41 mg/m^3) [9–11], these levels may still impact the operation of a mechanical vapor recompression (MVR) system used for steam compression to digestion pressures. To mitigate this, the current study proposes integrating a venturi scrubber upstream of the MVR unit for further removing fine particle, particularly those smaller than 2 µm, due to its high efficiency [12–14]. However, the energy requirements of such an integrated steam recovery configuration have yet to be quantified.

Given these technical and operational challenges, this study aims to conduct a comparative evaluation of steam recovery across four calcination pathways: natural gas/air, H_2/air, fully electrified and H_2 in oxy-steam calcination. The analysis focuses on net steam recovery rates, energy penalties from gas separation and cleaning, and the potential energy savings and CO_2 emission reductions in digestion through steam recovery integration.

2. Methodologies

2.1 Exit Flue Gas across Different Calcination Scenarios

Table 1 summarizes the flue gas compositions for four calcination pathways, based on process simulations performed in Aspen Plus. In conventional natural gas/air calcination, the flue gas comprises approximately 47 % N_2 and 9 % CO_2, together with 43 % steam. Switching to H_2/air combustion eliminates CO_2 emissions, however, the flue gas still contains 48 % N_2 introduced from air. In contrast, H_2 in oxy-steam calcination generates high-purity steam (above 99 %) and completely avoids nitrogen dilution by using pure oxy-steam combustion atmosphere, with recirculated superheated steam for solids transport. The fully electrified calcination eliminates combustion entirely, generates pure steam. The exhausted gas conditions from the calciner provide a comparative basis for evaluating the steam recovery potential from each calcination scenarios.

Table 1. Exit gas condition from calcination (with 120 t/h Al_2O_3 capacity).

		Scenario 1 Natural gas/air	Scenario 2 H_2/air	Scenario 3 Fully electrified	Scenario 4 H_2 in oxy-steam
Gas volume	m^3/s	87	90	85	85
Temperature	°C	165	165	176	167
Pressure (Absolute)	bar	1.06	1.06	1.06	1.06
Gas components (Mass Fraction)					
N_2	%	46.9 %	47.9 %		
CO_2	%	9.3 %			
O_2	%	1.1 %	4.2 %		0.8 %
H_2O	%	42.8 %	47.9 %	100.0 %	99.2 %
Total gas flow	t/h	210	205	159	163
Density of gas	kg/m^3	0.67	0.64	0.52	0.53

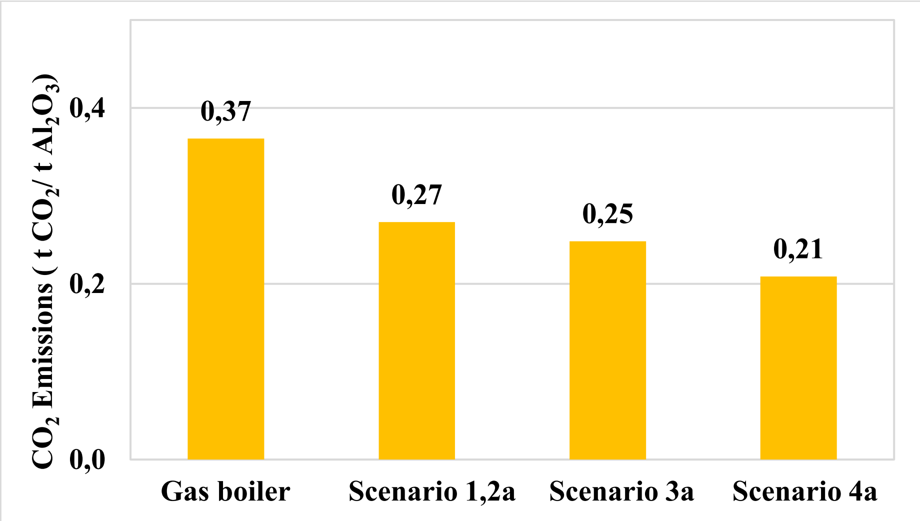

Figure 7. CO_2 emission in Scenarios 1a to 4a compared with natural gas boilers.

4. Conclusions

Integrating efficient steam recovery from air-combusted calcination, such as natural gas/air and H_2/air, can meet approximately 27 % of the steam demand in digestion, thereby reducing digestion energy use from 6.63 to 5.2 GJ/t Al_2O_3. Recovering high purity steam from fully electrified or H_2 in oxy-steam calcination can meet 32 % and 43 % of the steam usage respectively, reducing energy consumption to 4.8 and 4.2 GJ/t Al_2O_3. This corresponds to a CO_2 emissions reduction of 27–43 %. Compared to recovering diluted steam from air-combusted calciners, recovering pure steam demonstrates higher energy efficiency and yields a greater amount of recoverable steam. The process consumes 0.54 GJ/t steam for pure steam recovery, compared to 0.71 GJ/t steam for diluted steam recovery. Furthermore, replacing natural gas boilers with electric boilers achieves an additional 15% energy reduction, reducing digestion energy use to 3.6 GJ/t Al_2O_3 when incorporating steam recovery. The study highlights the potential of calcination steam recovery integration for both decarbonization and energy saving in alumina refining.

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