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Comparison of alternative flue gas dry treatment technologies in waste-to-energy processes

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ABSTRACT

Acid gases such as HCl and SO_2 are harmful both for human health and ecosystem integrity, hence their removal is a key step of the flue gas treatment of Waste-to-Energy (WtE) plants. Methods based on the injection of dry sorbents are among the Best Available Techniques for acid gas removal. In particular, systems based on double reaction and filtration stages represent nowadays an effective technology for emission control. The aim of the present study is the simulation of a reference two-stage (2S) dry treatment system performance and its comparison to three benchmarking alternatives based on single stage sodium bicarbonate injection. A modelling procedure was applied in order to identify the optimal operating configuration of the 2S system for different reference waste compositions, and to determine the total annual cost of operation. Taking into account both operating and capital costs, the 2S system appears the most cost-effective solution for medium to high chlorine content wastes. A Monte Carlo sensitivity analysis was carried out to assess the robustness of the results.

1. Introduction

Acid gases (HCl, HF, SO_2) are airborne pollutants typically generated in the combustion of solid waste. Their removal can be performed by several wet or dry treatment processes (European Commission, 2006). Best available techniques (BAT) for both approaches are able to meet current emission standards, but differ with respect to investment and operating costs. In particular, since their introduction in the mid-1990s, dry treatment systems based on sodium bicarbonate ($NaHCO_3$) injection have demonstrated cost-effectiveness and ease of operation and maintenance (Vehlow, 2015). About 29% of municipal solid waste incinerators (MSWI) built in Europe after 2000 adopt $NaHCO_3$ injection. In France and Italy sodium-based dry treatment systems are implemented respectively in 33% and 59% of the Waste-to-Energy (WtE) plants that started operation after 2005 (ISWA, 2012).

Recently, the need to combine the compliance to increasingly lower emission limit values with cost optimisation requirements has led to the development of novel solutions. In particular, dry treatment systems based on double reaction and filtration stages are an emerging technology, which has been adopted by several WtE plants in Northern Italy since 2006 (ISPRA, 2013). These two-stage systems carry out the removal of acid pollutants by two consecutive steps of neutralisation with alkali compounds (usually, calcium hydroxide in the 1st stage and sodium bicarbonate in the 2nd stage) and subsequent filtration for the capture of the solid residues produced by the reaction. However, in spite of their growing industrial importance, the experience with two-stage technologies is mostly empirical (De Greef et al., 2013) and scarce data are reported on the optimal performance of this process. In particular, the optimal integration of first and second stage to maximise efficiency and removal of acid gases still needs to be explored (Acquistapace et al., 2014), since the operational optimum depends on the concentration of acid pollutants in the flue gas and ultimately on the waste composition. Only recently Antonioni et al. (2014) developed an empirical model, which needs to be calibrated on actual plant data, in order to describe the acid gas removal efficiency of a two-stage (2S) system and to identify the configuration operating at the optimal economic performance, taking into account the costs for reactants and disposal of solid residues.

The aim of the present study is to assess the cost-effectiveness of a 2S system in comparison to single stage (1S) alternative processes. Three alternative 1S configurations (with electrostatic precipitator as pre-dusting equipment, with fabric filter as pre-dusting equipment, without pre-dusting equipment) all based on the injection of $NaHCO_3$, applied in several operating MSWI systems, were selected as benchmarking technologies. The sodium-based single stage dry alternatives may be considered as

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the most effective technologies presently adopted for acid gas removal in coupling emission standards compliance with low capital and operational costs (European Commission, 2006). Thus, 1S systems are the main market competitors of two-stage technology. In addition, 1S configurations with pre-dusting, as well as 2S systems, collect separately fly ash and sodium-based process residues. The separated sodium-based wastes can be processed in a dedicated plant to recover a brine suitable for sodium carbonate production (ISWA, 2008), thus minimising the amount of residues to be disposed of, which represents the main environmental drawback of dry acid gas removal processes.

The model proposed by Antonioni et al. (2014) was applied to assess the performance of both 2S and 1S processes. Given the input concentration of acid gases, calculated on the basis of different reference input waste compositions, the consumption of solid reactants and the production of solid residues needed to remove acid gases down to a target concentration were quantified. The model allowed a detailed simulation of the removal process, taking into account the non-linear relationship between reactant injection and acid gas abatement, as well as the selectivity of the solid reactants towards HCl and SO_2. In addition to the costs related to reactants and to residue disposal, also the investment costs and the other operating and maintenance (O&M) costs were estimated. The sensitivity of the results was tested with respect to changes in the major input parameters. The dependence of the costs on factors such as the Cl/S ratio in the waste, the required performance of acid gas removal and the variability of the cost entries was studied in order to provide a robust analysis for a wide range of operating conditions. Therefore, the flexibility of the alternative systems was assessed.

2. Materials and methods

2.1. Methodology adopted in the comparison of alternative technologies

A methodology was developed to allow the comparison of the total cost of operation of alternative dry technologies for acid gas removal from flue gas, given as input data the elemental composition of the waste feed and the required emission limits for HCl and SO_2. The methodology is summarised in Fig. 1. The composition of the flue gas leaving the combustion system, if not available from operational data, is calculated from the waste composition through a simplified mass balance approach. Given the concentration of the acid components in the flue gas and the required removal performance, the conversion model of Antonioni et al. (2014) allows quantifying the associated consumption of solid reactants and the generation of solid residues that need to be disposed. Eventually, the costs related to reactant purchase and solid residue disposal are summed to the annualised cost of equipment and to other ancillary costs (utilities, replacement parts, maintenance) to determine the total operating cost per annum of the treatment system.

The key point of the methodology is the application of the acid gas conversion model, tuned on actual operational data (Antonioni et al., 2014), which links the removal efficiency of the system to the actual ratio of reactant feed to acid pollutants load in the flue gas. This approach allows avoiding the use of fixed generic values of reactant feed rate per mass unit of waste, which are usually introduced in life cycle studies of air pollution control lines (Scipioni et al., 2009; Damgaard et al., 2010). Thus, the selectivity of the different solid reactants towards HCl and SO_2 is correctly taken into account.

In Section 2.2, reference process schemes are defined for each of the alternative technologies considered in the analysis. Section 2.3 reports the benchmarking data used for the comparison. Section 2.4 briefly describes the conversion model and Section 2.5 the data and assumptions used for the analysis of costs.

2.2. Reference technologies considered in the analysis

Fig. 2 shows the reference schemes defined to carry out a comparison among the two stage (2S) technology and the selected benchmark single stage technologies. The reference scheme of the 2S system shown in Fig. 2a can be considered representative of a typical 2S dry treatment system, and is based on the design of an actual plant located in Italy, described in detail elsewhere (Antonioni et al., 2014). The untreated flue gas flows in a reactor (actually, a ductwork designed in order to assure a given residence time), where the injection of a dry powder of calcium hydroxide ($Ca(OH)_2$, commercially known as hydrated lime or slaked lime) takes place. This alkaline material acts as a sorbent towards the acid pollutants, triggering the gas-solid reactions (R1)–(R3) reported in Table 1. The flue gas is then fed to a fabric filter, where the reactions continue on the filter cake of ash and powders deposited on the bags. Here, the solid products of the reactions (calcium-based wastes, CBW) are captured and removed from the flue gas stream. Part of the solids collected by the filter can be recycled to the reactor feed, since they generally contain unreacted lime. Eventually, CBW and ash are stored in a silo and sent to appropriate disposal sites. The second stage of the process consists of another reactor (a vertical Venturi-shaped pipe section) followed by a fabric filter, and its goal is to complete the removal of acid gases by the injection of sodium bicarbonate ($NaHCO_3$). Non-porous bicarbonate decomposes to porous carbonate with an almost instantaneous and complete process (see Reaction (R4) in Table 1) at temperatures above 130 °C (Brivio, 2007). Then, sodium carbonate reacts with the acid gases (Reactions (R5) and (R6) in Table 1). No solid recirculation is carried out, since sodium bicarbonate is much more efficient than slaked lime and very few unreacted particles can be found in the sodium-based wastes (SBW) collected by the fabric filter (Bodénan and Deniard, 2003). The collected SBW can be sent to a processing plant in order to recover a purified brine suitable as raw material in the sodium carbonate production process (Brivio, 2005; ISWA, 2008), thus reducing the mass of residues to landfill.

With respect to benchmarking technologies, the reference scheme of single stage treatment without pre-dusting (1S) consists in the injection of sodium bicarbonate through a Venturi-shaped reactor, followed by a fabric filter (Fig. 2b). Reactions (R4)–(R6) take place in the system and the process scheme itself is actually the same as the 2nd stage of the reference 2S system. Although listed among the BAT for acid gas abatement (European Commission, 2006), the 1S scheme has the drawback of not segregating SBW from fly ash. This prevents the possibility of recycling the SBW to produce sodium carbonate as described for the 2nd stage of the 2S system. Therefore, the 1S system is often integrated with a de-dusting stage prior to the injection of bicarbonate (pre-dusting, Fig. 2c). The pre-dusting device can be either an electrostatic precipitator (ESP-1S) or a fabric filter (FF-1S). 1S, ESP-1S and FF-1S configurations share the same approach to acid gas removal (Reactions (R4)–(R6)) and differ only in the investment and operating costs related to the pre-dusting equipment and in the consequent fate of the SBW.

2.3. Benchmarking data

In order to allow the benchmarking of the alternative technologies, some assumptions were introduced, and input data based on operating experience of actual facilities were defined. The same process specifications were applied to all the four alternatives