Mass and energy balance of NH4-salts pH swing mineral carbonation process using steel slag

GHGT-12

Mass and energy balance of NH$_4$-salts pH swing mineral carbonation process using steel slag

Marco Dri[a], Aimaro Sanna[a,*], M. Mercedes Maroto-Valer[a]

[a]Centre for Innovation in Carbon Capture and Storage (CICCS), School of Engineering and Physical Sciences,
Heriot-Watt University, EH14 4AS, Edinburgh, UK

Abstract

A basic evaluation of the entire NH$_4$-salts pH swing mineral carbonation process steel slag based system including CO$_2$ capture, ammonia absorption and regeneration of additives, has been investigated to evaluate its feasibility at industrial scale.
Heat released from mineral dissolution, pH adjustment and precipitation of impurities, carbonation reaction and CO$_2$ capture was 2.3 MWh/tCO$_2$ and could be recovered using heat exchangers and reused within the mineralization process to heat-up the incoming streams of steel slag, ammonium sulphate and water. Heat required, mainly from water evaporation and regeneration of additives, is reported to be 20 MWh/tCO$_2$.

Keywords: CCS, Mineral carbonation, Metal waste materials, energy balance

1. Introduction

Mineral carbonation by pH swing is a promising technology for the sequestration of carbon dioxide (CO$_2$) [1]. One of the advantages of mineral carbonation compared to underground storage is that it may take place at the same site, where CO$_2$ is released. An industrial process emitting CO$_2$ which could be retrofitted on-site with a mineralization facility is a steel plant, where CO$_2$ is emitted and an appropriate waste material is produced [2]. It should be noted that steel making and cement production industries are large emitters of CO$_2$, where emissions from the industrial sector are 20% of the total and steel making accounts for about a quarter of the industrial emissions [3].

---

* Corresponding author. Tel.: +44-(0)-131-451-3299.
   E-mail address: a.sanna@hw.ac.uk

The authors have previously studied dissolution and carbonation steps for NH_4-salts based mineral carbonation process using steel slag from one of the main steel plants in UK [4-5]. In this work, the entire process is investigated, including CO_2 capture, ammonia absorption and regeneration of additives, and mass and energy balance calculations are performed.

2. Methodology

The steel plant considered emitted 7.4 Mt/year of CO_2 into atmosphere which means 965t/h (assuming 320 working days per year) and steel slag production was 43t/h [6]. The mass balance was conducted considering the chemical reactions, reactants and products and their stoichiometric values. Steel slag was the chosen material because of the impact of steel industry on the global CO_2 emissions. From the reaction [4] and data on the CO_2 emissions and steel slag production of a specific steel plant, a mass balance for the mineralization process was performed. These calculations allowed assessing the quantity of chemicals required and products obtained and, consequently, investigate their impact on the mineralization process in terms of energy consumption. Afterwards, the energy balance of the overall process was performed. Heat released and required from each single step was calculated using the thermodynamic calculations (from HSC Chemistry 5.1) and the quantity of different inputs and outputs of each step of the process, obtained from the mass balance. After the investigation of the energy balance, the CO_2 emissions due to the process were calculated.
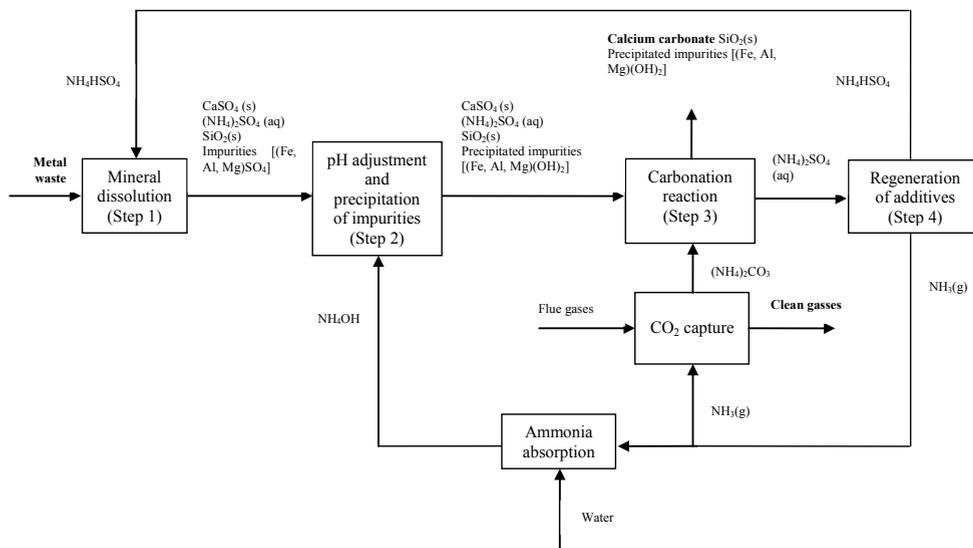

Figure 1 Multi-step close loop mineral carbonation process. [4].

3. Results and Discussion

Based on the chemical reactions reported in the previous works and the steel slag production of the plant considered (43t/h), a mineralization process with S/L ratio 15g/L able to sequester 13t/h of CO_2, employing all the steel slag produced, was developed.

The dissolution and carbonation steps of the mineralization process applied to the steel plant have a combined duration of 1.5 hour. The process takes place in a series of reactors of suitable size at S/L ratio of 15g/L and, because of the volumes of solution involved, most of the process equipment will consist of multiple plants operating in parallel.

Table 1 summarizes the energy balance, where negative values indicate heat released, while positive values represent heat required for each step. Results from the energy balance for each step of the process, obtained from the thermodynamic calculations and the mass balance indicate that the process investigated (mineralization system retrofitted into a steel plant) can sequester a theoretical maximum of 13t/h CO_2 (1.4% of the total emission) using 43t/h steel slag. The total heat released corresponds to 2.3MWh/tCO_2, while the total heat required is 20MWh/tCO_2. The highest heat demand is due to the water evaporation phase (18.6MWh/tCO_2). The regeneration step, instead, requires 1.8MWh/tCO_2, which is much lower than the value reported in a previous study for mineral carbonation with chemical regeneration using NaCl and HCl (3277 and 4361kWh/tCO_2, respectively) [7]. In comparison, direct mineral carbonation processes consume large amount of energy in the mineral activation stage (977kWh/tCO_2) and for recovering the employed chemicals (0.64M $NaHCO_3$ and 1M NaCl) [8]. Despite the large amount of water required (~2850t/h), it should be noted that the process can reuse it, and therefore, limiting the requirement of fresh water to 1t/h. Further work is required to decrease the energy consumption of the proposed process.

Table 1. Energy balance of the proposed mineralisation process applied to the steel plant, where 13 t/h CO_2 (43 t/h steel slag) are supposed to be captured.

Heat released	kWh
CO_2 capture	-14628
mineral dissolution	-12201
precipitation of impurities	-3549
carbonation	-100
Total Heat Released	**-30478**
Heat required	**kWh**
water evaporation (MVR)	242000
regeneration	22945
ammonium adsorption	131
Total Heat Required	**265076**

4. Conclusions

This work presented the mass and energy balance for the overall mineralization process in the case of sequestering 13t/h of CO_2 from a steel plant producing 43t/h of steel slag and employing a S/L ratio of 15g/l. Because of the close loop used, the impact of the quantity of NH_4HSO_4 and H_2O needed to be fed continuously into the system is small (1t/h for H_2O, and 0.3t/h for NH_4HSO_4). However, the total heat required of 20MWh/tCO_2 was very large and future work will be required to decrease the overall energy consumption of the proposed process. The highest heat demand is due to the water evaporation phase (18.6MWh/tCO_2).

Acknowledgements

References

[1] Kirchofer A, Brandt A, Krevor S, Prigiobbe V, Becker A, Wilcox J, Assessing the Potential of Mineral Carbonation with Industrial Alkalinity Sources in the U.S, Energy Procedia 2013;37:5858-5869.

[2] Kunzler C, Alves N, Pereira E, Nienczewski J, Ligabue R, Einloft S, Dullius J, CO_2 storage with indirect carbonation using industrial waste, Energy Procedia 2011;4:1010-1017.

[3] IEA, CO_2 emissions from fuel consumption: 2011 Highlights. Paris - France: IEA-International Energy Agency; 2011.

[4] Dri M, Sanna A, Hall MR, Maroto-Valer MM, Mineral carbonation from metal wastes: effect of solid to liquid ratio on the efficiency and characterization of carbonated products, Applied Energy 2014;113:515-523.

[5] Dri M, Sanna A, Hall MR, Maroto-Valer MM, Dissolution of steel slag and recycled concrete aggregate in ammonium bisulphate for CO_2 mineral carbonation, Fuel Processing Technology 2013;113:114-122.

[6] Holloway S, Vincent CJ, Kirk KL, Industrial carbon dioxide emissions and carbon dioxide storage potential in the UK. BGS sustainable and renewable energy programme commercial report, CR/06/185N, 2008.

[7] Teir S, Eloneva S, Fogelholm CJ, Zevenhoven R, Fixation of carbon dioxide by producing hydromagnesite from serpentinite. Applied Energy 2009;86:214-8.

[8] Gerdemann SJ, O'Connor WK, Dahlin DC, Penner LR, Rush H, Ex Situ Aqueous Mineral Carbonation. Environmental Science & Technology 2007;41:2587-93.