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Two-step accelerated mineral carbonation and decomposition analysis for the reduction of CO_2 emission in the eco-industrial parks

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ABSTRACT

Carbon dioxide (CO_2) emissions are a leading contributor to the negative effects of global warming. Globally, research has focused on effective means of reducing and mitigating CO_2 emissions. In this study, we examined the efficacy of eco-industrial parks (EIPs) and accelerated mineral carbonation techniques in reducing CO_2 emissions in South Korea. First, we used Logarithmic Mean Divisia Index (LMDI) analysis to determine the trends in carbon production and mitigation at the existing EIPs. We found that, although CO_2 was generated as byproducts and wastes of production at these EIPs, improved energy intensity effects occurred at all EIPs, and we strongly believe that EIPs are a strong alternative to traditional industrial complexes for reducing net carbon emissions. We also examined the optimal conditions for using accelerated mineral carbonation to dispose of hazardous fly ash produced through the incineration of municipal solid wastes at these EIPs. We determined that this technique most efficiently sequestered CO_2 when micro-bubbling, low flow rate inlet gas, and ammonia additives were employed.

Introduction

Rapid urbanization and anthropogenic disturbance have resulted in various environmental challenges. One major challenge is the threat of global climate change, intensified by the release of greenhouse gases (GHGs) generated as wastes and byproducts of anthropogenic activities, such as the large-scale burning of fossil fuels. Global climate change is predicted to have drastic, negative impacts on natural meteorological patterns and ecosystem functioning as well as on human economic activities (IPCC, 2007).

Carbon dioxide (CO_2), produced primarily through fossil fuel consumption and urbanization, is one GHG known to be a main contributor of global climate change, resulting in an increase in the average surface temperature of the Earth since the beginning of the Industrial Revolution (IPCC, 2007).

As a result of international cooperative agreements like the Kyoto Protocol outlined by the United Nations Framework Convention on Climate Change, many countries have adopted policies aimed at reducing CO_2 emissions; the European Union plans to reduce GHGs to 20% of 1990 levels while the USA and Japan have pledged to reduce levels to 17% and 15%, respectively, of 2005 levels by 2020 (PCGG, 2009). In addition, countries not considered as one of the 37 Annex I countries under the Kyoto Protocol have also pledged to reduce CO_2 emissions. For example, South Korea, which is the 9th largest producer of GHGs in the world (IEA, 2011), plans to reduce GHGs to 30% of the business as usual (BAU) level by 2020 and to focus on environmentally-friendly industrial development strategies under a slogan of “Low Carbon, Green Growth” (PCGG, 2009).

In accordance with the seriousness of the threat of GHGs to the environment, a great deal of research has focused on factors influencing CO_2 emissions and on the development of strategies used to mitigate those emissions. One strategy currently being employed in South Korea is the use of eco-industrial parks (EIPs),

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defined by the United States President's Council on Sustainable Development (PCSD) as "a community of businesses that cooperate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat), leading to economic and environmental quality gains, and equitable enhancement of human resources for the business and local community" (PCSD, 1996). Under the EIP concept, various techniques are employed to efficiently use space and resources while minimizing the production of waste products. The EIP initiative has been attempted as a way to reduce CO_2 emissions by both developing and developed countries worldwide, including Europe (Baas and Boons, 2004; Tudor et al., 2007), China (Fang et al., 2007; Zhang et al., 2010), the USA (Gibbs and Deutz, 2005, 2007), Australia (Roberts, 2004), and Japan (Berkel et al., 2009). In South Korea, existing industrial complexes, which have played pivotal roles in economic growth since the 1960s, are being converted into EIPs. Industrial complexes historically served as export outposts, magnets for large-scale installation industries, and as a means of fostering growth in rural areas (KICOX, 2008). However, with continuing urbanization and the downturn of the global economy in the 2000s, many companies that were part of these industrial complexes went bankrupt after significantly aggravating environmental problems through poor production methods (KICOX, 2008). As a result, the Korean Ministry of Knowledge Economy (MKE) promoted the EIP initiative beginning in 2005 as a way of reducing pollutants while maximizing the efficient use of energy and resources. To date, large industrial complexes have been replaced by EIPs in the South Korean cities of Ulsan, Banwol, Chungju, Yeosu and Pohang. Up to now, these industrial complexes have been emitting much more CO_2 than surrounding areas when per area emission is considered (**Fig. 1**).

However, after converting into EIPs, many waste products produced in these complexes are reused or eliminated through exchange of byproducts and gas incineration, further reducing CO_2 emissions.

In addition to the general use of EIPs in reducing the negative environmental impacts of industry, EIPs can employ efficient technologies to further reduce their, and ultimately the entire country's environmental impact.

The IPAT equation describes the impact of human activity (I) on the environment as a function of population (P), affluence (A) and technology (T) where $I = P \times A \times T$. The IPAT relationship indicates that, among other strategies, effective technological choices can help to reduce a country's environmental impact per unit of economic activity (Song et al., 2011). For example, some environmentally-friendly technologies can reduce CO_2 emissions by improving CO_2 fixation, utilization, and sequestration (Ahn et al., 2010). One such technological advancement, accelerated mineral carbonation, has recently received attention for its ability to rapidly sequester CO_2, which is especially valuable in countries like South Korea where small land mass limits the amount of CO_2 that can be naturally stored in geological features (Khoo et al., 2011). EIPs typically use incinerator techniques to burn municipal solid waste (MSW) products, which produce a hazardous fly ash that is often too expensive to dispose of with recent landfill taxes (Li et al., 2007). Accelerated mineral carbonation can be used to stabilize solid residues generated from coal-fired power plants as well as other types of combustion residues (*e.g.*, MSW ashes) that make their disposal safer and more cost effective (Rendek et al., 2006).

Although many researchers support the effectiveness of accelerated mineral carbonation of MSW ashes (Ahn et al., 2010; Baciocchi et al., 2009a, 2009b; Gunning et al., 2010; Li et al., 2007; Montes-Hernandez et al., 2009; Rendek et al., 2006; Wang et al., 2010), most carbonation technologies researched in the past used pure CO_2 as the emission being processed despite the fact that the amount of CO_2 in emissions produced through MSW incineration is typically only around 12% (Jiang et al., 2009; Rendek et al., 2006).

In this article, our objectives are to: (1) analyze the characteristics of CO_2 emissions from EIPs, and (2) examine the efficacy of accelerated mineral carbonation of gases representative of those actually produced through the incineration of MSW (specifically those containing CO_2).

1. Materials and methods

1.1. EIP characteristics of South Korea

The implementation process of the South Korean EIP initiative is divided into three phases. The first phase (2005–2009) of the development plan strived to implement trial projects, whereby industrial complexes were transformed into EIPs armed with a baseline understanding of material and energy flows, and byproduct and waste generation.

The second phase (2010–2014) has been planned to provide conceptual ideas and disseminate the understanding of the concept to surrounding industrial parks. It would also help in increasing the number of EIPs and sustaining a balance between the different key factors that are likely to influence economic growth.

The third phase (2015–2019) would analyze any flaws and constraints that may arise after the implementation of the earlier phases. The lessons learnt would be fed back into the system/plan, so as to tweak it. The third phase would essentially help perfect the South Korean EIP model.

After finishing the first phase, each EIP is having its own characteristics now. Ulsan EIP focuses on higher, value-added products and steam network businesses (KICOX, 2008). For example, a company produced 10 wt.% of zinc powder that did not meet the criteria of the painting industry's zinc powder fabrication process. This company then made a higher value-added flake-type zinc powder using zinc dust. Similarly, an incineration plant sold steam from electricity generation to the other factories. This steam replaced bunker C oil energy with steam energy. Furthermore, in order to maximize the value of the steam, other factories that could utilize steam were constructed.

The representative project in the Yeosu EIP is a hydrogen exchange network, which facilitates the exchange of hydrogen gas among a network of companies based on purity (KICOX, 2008). This project is considered highly efficient, especially given currently high oil and raw material prices (*e.g.*, naphtha, liquefied petroleum gas (LPG), and liquefied natural gas (LNG), which accounts for 70%–80% of the unit costs of production).

The Banwol EIP is composed of variety of small chemical companies (KICOX, 2008). A pilot project in this EIP devised a recycling network that recovered copper powder using an electrolytic recovery system with the circulation of waste copper chloride solutions.

Finally, representative projects in the Chungju EIP involve waste acid networks through solidification treatments, and projects at the Pohang EIP involve the development of new alternatives to steel.

1.2. Factor decomposition using LMDI analysis

An understanding of the characteristics of CO_2 emissions is critical for controlling and mitigating their release (Zhang et al., 2011). We used the Logarithmic Mean Divisia Index (LMDI) method for analysis. This method has previously